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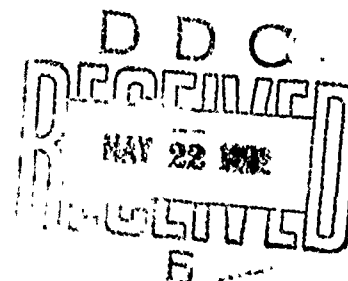
PERFORMANCE OF TREES AS RADIO ANTENNAS
IN TROPICAL JUNGLE FORESTS
(PANAMA CANAL ZONE EXPERIMENTS)

Kurt Ikrath
William Kennebeck
Robert T. Hoverter

February 1972

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Kurt Ikrath
William Kennebeck
Robert T. Hoverter

Propagation (NB) Technical Team
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ABSTRACT

Radio transmission and reception experiments in tropical jungle forest covered terrains are described and the performance of conventional whip antennas is compared with the performance of Hybrid Electromagnetic Antenna Couplers (HEMAC) in conjunction with jungle trees as antennas.

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Introduction

"It would seem that living vegetation may play a more important part in electrical phenomena than has been generally supposed. If as indicated above in these experiments, the earth surface is already generously provided with efficient antennas which we have but to utilize for communications." These words were written in 1904 by Major George O. Squire, US Army Signal Corps, in a report to the US Department of War in connection with military maneuvers in the Pacific Division; in a June 1919 article entitled "Tree Telephony and Telegraphy," published in the Franklin Institute Journal, Major General Squire, Chief Signal Officer, US Army, reported on the role of trees as long wave receiver antennas. Fifty years later, in the summer and fall of 1969, the trees in New Jersey were employed again by the US Army Electronics Command to work as antennas; in this case, the trees were used as transmitter antennas for frequencies ranging from medium to short wavelength. In the present application, the tree trunk was given the role of acting as a single turn low impedance secondary winding in a resonant toroid type transformer wherein the primary winding is a flexible spiral spring that is wrapped around the tree trunk. When stretched out completely, the toroid degenerates into a 24 foot long electrical wire antenna; and when pushed together, it becomes a multiturn magnetic loop antenna of about an 8 inch coil diameter. Because of its intrinsic electrical and magnetic properties, the toroid was given the name HEMAC, an acronym for Hybrid Electromagnetic Antenna Coupler. With 12 watts RF power and at frequencies between 4 and 5 MHz, transmission ranges from 7 to 11 miles were achieved using HEMAC toroid coupled oak and pine forest trees for transmission and a vertical whip antenna for reception; at frequencies of 425 kHz and 460 kHz and with about 35 watts RF power transmission, ranges from 30 to 35 miles were obtained using very large oak trees coupled by a larger HEMAC toroid. Furthermore, as demonstrated by HF radiation patterns from differently oriented natural tree loops in the Lebanon N.J. State Forest and by the MF radiation patterns from large oak trees near swampy water-filled gullies, the interaction of the HEMAC toroid coupled tree with its immediate neighbor trees and local terrain features can be exploited to enhance respectively HF and MF signal emissions into desired geographic directions.^{1,2}

However, the deciduous forest in New Jersey is only a poor substitute for the actual tropical jungle forests, in which ferns and palms grow as tall as trees, and which present a great obstacle to tactical radio communications which use conventional whip antennas. In order to evaluate the ability of a HEMAC to overcome these obstacles, the PRC-74 tactical radio set was chosen to accommodate an impedance matchbox designed to connect the antenna terminals of the PRC-74 set with the toroid coupled tree (Fig. 1), and which will provide a match to the empirically determined equivalent series tuned load impedances of pine and oak trees ranging from about 1.5 ohms to approximately 5 ohms. (Figs. 2 and 3.)

Synopsis of Panama Canal Zone Experiments (Aug-Sept 71)

1. Vegetation and Terrain

The jungle forests in the Panama Canal Zone do not have a dense and closed canopy (Fig. 4), but are actually formed by an impenetrable dense underbrush vegetation (Fig. 5) which gives the trees little opportunity to grow tall and high; large trees, ranging in height from about 50 to 100 feet, can be found but they are spaced much farther apart than similar large trees would be in a typical New Jersey forest. Also, the trunks of jungle trees rarely exceed two feet in diameter, except along trails and roads which are cleared regularly of the fast growing underbrush vegetation. The trunks of jungle trees are fungus infested and covered by moss so that the surfaces are often spongy soft and rotten; however, the wood tissues beneath the surface are hardened by the osmotic pressure of the sap and water which swells the lower parts of the trunks of some trees and ferns during the rainy season. Among the many different jungle trees which were used during the experiments conducted in the Chiva Chiva and the Gamboa A2 test areas of the US Army Tropical Test Center, some could be identified by their scientific and common names:

Cavanillesia platanifolia = Guipo

Pseudobomax barrigon = Powder puff tree

Spondias mombin = Jobo, Spanish plum

Inga spuria = Guave

The terrain in the test area was hilly, the soil was reddish loam which lends its reddish color to the many creeks in the area which turn into streams during the daily torrential rain and thunderstorms that are characteristics of the rainy season. Thunderstorm activity and heat lightning which occur daily are responsible for unusually high radio noise that interferes with radio communications. This kind of fast changing atmospherical noise seems to be one of the major problems for tactical radio communications in the tropics.

2. Experimental Results

The major part of the experimental results can be summarized as follows: Using the vertical whip of the URM-85 RFI Analyzer - Field Strength Meter for reception in jungle clearings (Fig. 6) of 4.650 MHz, * signal emissions from HEMAC toroid coupled jungle trees (Fig. 7), the toroid by itself in air (Fig. 8), and the PRC-74 (Fig. 9), the following results were obtained with the same PRC-74 set as transmitter:

a. (Fig. 10) Signal field strengths from toroid coupled jungle trees are about equal to those from the whip, if vegetation surrounding the whip is removed by machete within a minimum range of $\frac{1}{2}$ foot; if, however,

* Authorized frequency assignment.

only a single leaf touches the whip slightly, its radiated field strength falls off by about 20 dB, in spite of the fact that under these conditions the PRC-74 set is readjusted for apparently full available input power into the whip as indicated by the PRC-74 output meter. It should be noted that since it is very difficult to see the green colored PRC-74 whip in the green darkness of the jungle, such a condition could occur easily during tactical situations in the field.

b. Signal field strength received from the toroid by itself in air is about 15 dB lower than that from the toroid coupled trees, which proves the role of the trees as radiating elements.

In this connection, it is necessary to mention that optimum match and full available RF power input into toroid coupled jungle trees could not be obtained with the series tuned matchbox circuit which had been designed on the basis of experience with oak and pine trees in New Jersey, evidently the impedances of tropical jungle trees are different from those of hard and softwood trees in New Jersey. Within the existing limitations imposed by the tropical environment, the impedance variation was verified by improvising a parallel tuned matching circuit in which the toroid on the tree operates as an autotransformer (Fig. 11). The equivalent series resistances of toroid coupled jungle trees were found to be 3 to 4 times larger than those of the oak and pine trees in New Jersey. The corresponding improvement of the match between the toroid coupled jungle tree and the PRC-74 set showed up as a 5 dB gain in the emitted signal strength measured with the vertical URM-85 whip; accordingly, this gain would be reflected in the data (Fig. 10) by raising the toroid coupled tree emissions by 5 dB over the whip emissions; further improvements are certainly possible in view of the fact that the improvised circuit provided only a better match and not an optimum match.

By reciprocity, the significance of the matching conditions is recognized from the data obtained with a toroid coupled tree as a receiver antenna (Fig. 12). In this case, using a cable impedance isolation Field Effect Transistor (FET) circuit with 6 dB voltage loss (Fig. 13) to connect the URM-85 meter with the parallel tuned toroid coupled tree, the latter outperformed the 12 foot high URM-85 whip (Fig. 14) by 12 to 22 dB.

Yet, the existing mismatch between PRC-74 set and series tuned toroid coupled jungle trees becomes insignificant when one receives over increasing distances by horizontal dipole antenna (Fig. 15) signals emitted from the PRC-74 whip and from toroid coupled jungle trees which are powered by the same PRC-74 set. Signals transmitted on 4,000 MHz over increasing distances from different mismatched jungle tree radiators increased to over 8 dB above those emitted from the whip (Fig. 16). The deterministic nature of these data from the spatially limited Chiva Chiva Test Area and the advantage relative to the portable whip of immobile jungle trees was clearly established by measurements of the decay of 4.650 MHz CW-signal levels as functions of distance from toroid coupled tree and whip transmitter antennas in the Gamboa Test Area in Panama (Fig. 17, 18, 19): Even without the detailed description of the measurement procedures which are given in the subsequent part of this report, one recognizes that wetness (Fig. 18) and dryness (Fig. 19) of the vegetation, and changes from dry to wet during a thunder-

storm (Fig. 20), are associated with significantly different shapes of the CW signal decay versus distance curves, i.e., the signal to noise ratios (Figs. 21 and 22), measured with the whips and with toroid coupled trees (Figs. 23 and 24).

In particular, the combination of local terrain features, wetness of the vegetation, and atmospheric noise which shaped the signal decay curves are responsible for the loss of voice communications by whip equipped PRC-74 sets between the transmitter and the receiver party, over distances from 1 to 2 miles, where the signals were received well above noise using toroid coupled trees as antennas. The greater susceptibility of the whip to performance degradation by obstructing features of the terrain and vegetation was observed also during qualitative tests; for example, in a .6-mile transmission test from Chiva Chiva to Gamboa, with 15 watt input power into the PRC-74 whips, several signal fadeout locations were encountered in the hilly terrain, particularly along the road in Gamboa and similar jungle clearings. With a toroid coupled jungle tree as radiator (Fig. 25) in the Chiva Chiva Area, a 10-mile range was achieved with about 20 watts of RF power; were it not for the radio interference noise from the power line which runs parallel to the Canal, probably a larger transmission range would have been possible. This assumption was confirmed indirectly in the Gamboa jungle area where signals emitted from the toroid coupled tree at Chiva Chiva were received by PRC-74 sets everywhere along the road and on the Las Cruces Trail (Fig. 26) with series tuned (mismatched) toroid coupled trees and also with the PRC-74 whip; replacing the series tuned toroid matchbox circuit with the previously mentioned parallel tuned impedance transformation FET circuit strength and clarity of reception by trees of our own 4.650 MHz emissions from Chiva Chiva as well as of an adjacent voice station on 4.555 MHz was further increased. Similarly, using a series tuned toroid coupled tree (Fig. 27) on the Las Cruces trail in the Gamboa jungle area, foreign HF radio broadcast stations (Radio El Sol Costa Rica, 6.006 MHz) were received loud and clear in spite of high atmospheric noise from a developing thunderstorm.

By comparison with wet fungus infested moss covered jungle trees, a man planted palm tree, the Prince of the "Vegetable Kingdom" turned out to be a 7 dB more lossy HF antenna, in spite of its isolated location relative to other palm trees and in spite of its clean and hard trunk. The result, which is subject to further confirmation, tends to agree with the expectation that vegetable and ferns are by virtue of their structure less efficient HF radio antennas than are the trees.

The inherently wide band HF to MF radio emission capabilities of jungle trees was confirmed; 410 kHz (i.e., 750 meter) keyed CW signals emitted from a large toroid coupled jungle tree at Chiva Chiva (Fig. 28) were received well above noise with an HRO 500 receiver and a whip of only two meter length in the Gamboa area about 6 miles away. In this case, primary RF power was 30 to 40 watts.

3. Improvements for HEMAC Toroid and Whip

The dimensions and configuration of forest trees are assets with regard to radiation efficiency; poor conductivity and structure of tree trunks are liabilities, particularly in the RF emission case where local concentrations of strong fields are unavoidable. In Panama, another liability turned out to be the rather thin plastic insulation of the toroid conductor against the moss and fungus covered soft surfaces of tree trunks. By analogy with a transformer, this is equivalent to having a large detrimental capacity between the primary and the secondary winding; hence the electrical performance improvement of the HEMAC toroid involves simply increasing the insulation. Also, the impedance matching range of the matchbox should be shifted upward for operation with jungle trees from about 1.5 to 5 ohms to about 3 to 15 ohms.

The whip must also be insulated to avoid the detrimental galvanic contacts with the vegetation.

These improvements will enlarge the overlap between the useful application ranges of the direct and the indirect leakage radiation mechanisms for the whip and toroid coupled trees, but will not change the following conclusions.

Conclusions

The results of the Panama jungle experiments and measurements could be summarized best as follows: For tactical radio communications in jungle terrain, operate on lower HF and higher MF frequencies (e.g., Marine band) and continue to use a whip, but have a HEMAC toroid available so that when the whip cannot be used efficiently you can still establish communication by using HEMAC coupled trees.

Recommendations

a. Applications of Medium Frequencies

The performance of forest trees as radio antennas makes medium frequencies (300 kHz to 3 MHz) practical for tactical purposes. For example, in view of the insensitivity against scatter and attenuation in rough terrain and vegetation and the related greater penetration into earth and water, medium radio wave signals emitted by forest trees could play an important role in remote control of buried and submerged devices. Hence, it is recommended to demonstrate in the field the activation and deactivation of mines in forest covered terrain by MF ground waves, which are emitted and received by toroid coupled forest trees.

b. Directivity of HF Radiation from Forest Trees

The existence of intrinsic directivities of radiation patterns from HEMAC toroid induced natural tree loops associated with the heterogeneity of forest vegetation has been verified before. The next step amounts to controlling the directivity of HF radiation from trees by array techniques.

Hence, it is recommended to design appropriate circuitry for this purpose and to measure in the field the degree of control over the directivity of HF radiation from pairs of toroid coupled forest trees with respect to elevation and geographic direction.

c. Tree Coupled Radio Repeaters

It is customary to install radio repeaters on mountain tops to overcome terrain obstacles. The vulnerability of such repeater installations is self evident. Forest trees, however, can perform such a job easily and most of all invisibly; for these reasons, it is recommended to develop simple, light weight, expendable XMTR and receiver packages operating from about 1.5 to 4 MHz for use with toroid coupled trees on opposite slopes of a mountain.

d. Atmospheric Radio Noise

Heat lightning, thunderstorms, and related atmospheric phenomena are the main sources of natural radio noise in the tropics. It appears that their detrimental influence on radio communications is to some extent caused by susceptibility of electrical whip antennas to local electrical noise field gradients of atmospheric origin. Hence, it is recommended to investigate this susceptibility and to improve antennas and receiver input circuits accordingly.

Acknowledgments

The exploitation of tropical jungle trees as radio antennas is a part of an In-House Research and Development program which has been guided by Col. J. P. Dobbins and Col. J. D. Mitchell, Directors of the US Army Electronics Command Comm/ADP Laboratory.

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1. K. Ikrath, et al, "Exploitation and Performance of Forest Trees as Antennas for Radio Communications in Dense Forest Covered Terrains, (Lebanon State Forest N.J. Experiments, Sep-Oct 69)," Research and Development Tech Report, ECOM-3343, AD 880-935, Oct 70.
2. K. Skrivseth, "Signal Propagation at 400 kHz Using an Oak Tree as Antenna," Research and Development Tech Report, ECOM-3504, Sep 71.

APPENDIX A: QUALITATIVE TESTS

- A.1 Reception in jungle vegetation of foreign HF broadcast stations with PRC-74 set using a HEMAC toroid coupled jungle tree as antenna (Aug 30, 1971 - afternoon).

Result: Radio El Sol , Costa Rica comes in loud and clear on the Las Cruces jungle trail with the PRC-74 set tuned to 6.006 MHz (Fig. 27). (This station was identified by Capt. Alaiza who speaks Spanish fluently.) Other Spanish stations were also received between 5 and 7 MHz but were not identified.

Observations: The bigger trees in the area are 90 to 100 feet high and much further apart from each other than in the N. J. forests Wayside Test Area and Lebanon State Forest. Contrary to expectation, there is no really dense canopy but an extremely dense underbrush vegetation.

Tree trunks are wet, soft, and rotten, so that the hook on the velcro belt mounted toroid does not hold. Radio interference from atmospheric noise, spherics, is extremely strong by comparison with N. J. with both the tree and the whip as antennas.

- A.2 Voice communications on 4.650 MHz (authorized frequency) between Las Cruces jungle trail locations (Fig. 26) and various points on the road through the Gamboa A-2 Test Area up to 2 miles northeast and southwest from its intersection with the Las Cruces jungle trail (Fig. 17).

Results: Using one PRC-74 set connected via series matchbox to a toroid coupled tree and directly to the PRC-74 whip at the Las Cruces trail site and another PRC-74 set with its whip antenna on the road points, voice transmission and reception on both ends was loud and clear in spite of high spherics from increasing thunderstorm activity.

Observations: Receiver gain settings for the whip set on the road at the 2 mile points were approximately 2/3 and 80% of full gain for about equal voice loudness with respectively the whip and the jungle tree as radiators on the jungle trail site. The gain setting of the set at the jungle trail site was kept fixed when changing from tree to whip radiator, with maximum gain set at about 2/3 of full available gain for the 2 mile points. Voice transmissions from HEMAC toroid coupled tree appeared slightly distorted compared to transmissions from the whip. On CW, no more than 0.75 A RF through the toroid on the tree (about half of the toroid current obtained with oak and pine trees in N. J.). Thunderstorm and heavy rain forces termination of test somewhat prematurely.

- A.3 Maximum Signal Transmission Range

- a. Voice and CW tone communications on 4.650 MHz between PRC-74 with whip setup on concrete platform near building at the Chiva Chiva Test Area and PRC-74 set with whip on Landrover vehicle and off the vehicle on the road (Sep 9, 1971 - morning).

Results: Achieve 6 mile range, Chiva Chiva to Gamboa Test Area with 410 mA RF whip footpoint current at Chiva Chiva and full gain setting in the transmission and reception mode.

Observations: There is less atmospheric noise in the morning; power line RFI noise along the road parallel to the canal is very severe compared to similar power line RFI in N. J. Reception of voice and CW tone signals from Chiva Chiva fades out on the jungle road in the Gamboa Test Area between 1. to 2 miles from the entrance gate. (See map, Fig. 17.)

- b. Keyed CW signal transmission on 4.650 MHz using as an antenna one of the large trees on the banks of the creek running through the Chiva Chiva Test Area (Fig. 25) (Sep 3, 1971 - afternoon.)

The HEMAC toroid used to couple to this tree was fed in this case from a lab constructed single tube novice transmitter attached directly to the toroid. (In this transmitter setup, the HEMAC toroid coupled tree forms the load impedance in a PI network which is tuned by input and output shunt capacitors.) On the basis of equivalence with a 5 ohm dummy load, the power input into the toroid corresponding to 2.0 A of RF drive current is estimated with about 20 watts.

Results: Using a PRC-74 set with its whip on the road for reception, the signal transmission from Chiva Chiva was received up to 10 miles distance along the road, parallel to the Panama Canal, approximately 3 miles past the entrance to the Gamboa Test Area. At 10 miles, the signal reception was lost due to strong interference from powerline noise rather than from spherics.*

Turning back and entering the Gamboa Test Area (Fig. 17), the 4.650 MHz signal was picked up with the PRC-74 set about equally well above noise using the PRC-74 whip and toroid coupled jungle trees connected via series tuned matchbox to the PRC-74 set at various locations on the road and on the Las Cruces Jungle Trail in the vicinity of its intersection with the road (Fig. 26 and 27).

Replacing the series tuned toroid matchbox with the parallel tuned cable isolation FET amplifier (Fig. 13), led to further improvement in strength and clarity of reception of both our 4.650 MHz signals from Chiva Chiva and of voice from an adjacent 4.555 MHz radio station.

Observations: Landrover vehicle produces ignition noise and its engine had to be turned off for clear voice signal reception by whip on the jungle road.

- c. Keyed CW signal transmission on 410 kHz (i.e., $\lambda = 750$ meter) from toroid coupled tree at Chiva Chiva.

Using one of the larger trees in the Chiva Chiva Test Area as antenna powered via the large 400 to 500 kHz toroid from a Kronhite Amplifier

* Corona over insulators on the high tension line parallel to the Canal appears to be responsible.

and HP 200 CD Generator (Fig. 28), a similar 6 mile transmission range, Chiva Chiva to Gamboa was achieved with only a 2 meter long receiver whip (at a wavelength of 750 meters) on the Landrover vehicle and an HRO 500 Radio Set with LF converter (Fig. 29).

Observations: In contrast to the HF transmissions from the whip, much smaller fluctuation of the received signal strength as function of spot locations, particularly, on the jungle dirt road in the Gamboa Test Area were experienced; whereas, power line interference on the road to Gamboa appears to be stronger in some areas than in the HF case.

APPENDIX B: MEASUREMENTS AT THE CHIVA CHIVA TEST AREA

B.1 Broadside type radiation from a 15 meter long horizontal wire dipole antenna versus radiation from the PRC-74 whip on 4.650 MHz (1 Sep. 71.)

Setup: Using in both cases the PRC-74 Radio Set to power the horizontal wire and the whip at full available antenna input (as indicated by the PRC-74 output meter), the respective field strength levels were measured with a URM-85 Interference Analyzer at a location in a jungle clearing about 0.2 mile from the following transmitter locations:

- a. In a hole cut with machetes into the dense underbrush of the jungle.
- b. On a dirt road about 100 feet from the hole.

The horizontal wire dipole was suspended between trees using plastic insulators. Resonant operating conditions for the horizontal wire antenna, inclusive of its Balun, were obtained by adjusting the height of the antenna to about 5 and 8 feet above the muck of the jungle and the surface of the dirt road, respectively. * Measurements were made separately with only the horizontal wire and only the whip present to avoid possible passive interaction between these antennas.

Results: Received noise level is 10 dB rel. 1 microvolt. With the whip driven with 410 mA, RF signals radiated from the jungle hole location come in at 63 dB rel. 1 microvolt. The horizontal wire dipole driven with 310 mA RF at the jungle hole site and with 318 mA RF at the road site produces 52 and 56 dB rel. 1 microvolt, respectively.

Observation: It takes a lot of time and effort to setup a long horizontal wire antenna in the jungle, and touching contacts between the wire and the vegetation cannot be avoided without cutting a few rather thick ferns and trees..

B.2 Decays with distance of 4.000 MHz signals emitted from the whip and from HEMAC toroid coupled jungle trees (26 Aug 71.)

Setup: Jungle trees, evidently softwoods like cotton and panama trees, located within dense underbrush vegetation were powered by toroid from a PRC-74 set. Used with its whip, the set was placed a few feet away from the toroid coupled trees. Vegetation within less than 1 foot from the whip was cut away by machete.

Through adjustment of the matching and tuning controls on the PRC-74 set, full scale power output indication on the PRC-74 output meter was achieved with the whip as antenna at each spot location. Similarly, with the toroid coupled trees connected via series tuned matchbox to the PRC-74 set, the tuning capacitor of the matchbox and the PRC-74 control knobs were adjusted for relative maximal RF current flow through the toroid; e.g., 1.00 A on the first tree, 0.75 A on the second tree and again 1.00 A on the third most distant tree. **

* In oak and pine woods in New Jersey, resonance frequencies of the dipole with and without balun ranged from 3.4 MHz to 6.8 MHz.

** These toroid load current levels are about 50% of those achieved with oak and pine trees in N.J.

The corresponding maximal readings on the PRC-74 output meter were about 50% to 70% of full scale.

Signals radiated from the whip and from the toroid coupled jungle trees were received with a horizontal wire dipole antenna and an HRO-500 receiver (Fig. 15). The strengths of the received CW signals as displayed on the HRO-500 S-meter were measured using an HF signal generator as substitution standard.

Results: Using 150 microvolts as the zero dB reference, the signal levels produced by respectively the toroid coupled tree and the whip radiators are plotted in Figure 16 as functions of the distance to the horizontal dipole receiver antenna. The relatively low reference level of 150 microvolts is due to the fact that this horizontal dipole antenna was designed for the 40 meter band and not for 75 meter (4.000 MHz) signal reception. This explains to some extent also the relatively high level of the received heat lightning noise which is indicated on the ordinate in Figure 16.

Considering the spatial limitations in the Chiva Chiva Test Area and the corresponding small number of data points, the lower attenuation of signals from the toroid coupled trees could be dismissed as a statistical freak; however, the subsequent measurements in the Gamboa jungle area proved the deterministic nature of the divergency between whip and trees with regard to signal decays as function of distance between XMTR and receiver; a similar divergency has also been observed with different types of antennas in microwave modeling experiments where grasses, herbs, and shrubs were used to model RF scatter in jungle forests.

B.3 Transmissions of 4.650 MHz CW signals from PRC-74 whip, toroid coupled jungle trees, the toroid by itself in air and reception by vertical whip and toroid coupled jungle trees. (Aug 31, Sep 1 and 3, 1971.)

Setup: Two different trees at different XMTR locations were used; one tree at the previously mentioned jungle hole site (Fig. 7), the other tree at the edge of a dirt road (Fig. 11) about 50 feet from the jungle hole.

Transmissions on 4.650 MHz were carried out using as radiators the PRC-74 whip (Fig. 9), the toroid coupled jungle trees at the jungle hole and the road locations, and the toroid by itself in air on the road.

The toroid by itself in air setup is seen in Figure 8. In this case, the toroid is wrapped on a horizontal cardboard ring which is mounted on a box.

Pictures of the receiver setups in a jungle clearing approximately 0.2 mile of the transmitter locations are shown in Figures 6, 12, and 14. The URM-85 RFI analyzer-field strength meter is used here to measure signal strengths with the URM-85 whip and with a toroid coupled jungle tree as receiver antennas. The URM-85 whip connects to a whip to coax cable impedance matching transformer on top of a wooden tripod (Fig. 14). The output of this transformer is connected with a 4 meter long cable to the URM-85 meter. In the toroid coupled tree receiver case, the URM-85 whip and

and its matching transformer are replaced by the toroid on a tree at the edge of the jungle clearing and a lab constructed toroid to cable impedance isolation FET amplifier.* The transformation via the FET amplifier from the high impedance of the parallel tuned toroid coupled tree circuit to the nominal 50 ohm input impedance of the coax cable and of the URM-85 meter involves a 6 dB loss in voltage.

Results: The measurements are illustrated and the resultant data are listed in a flow chart type diagram in Figure 10.

Numerical data in the flow chart diagram give the Signal + Noise to Noise Ratios ($\frac{S+N}{N}$) in decibels as they were received with the URM-85 RFI field strength meter. The associated absolute noise levels in dB above one microvolt (dB/1 μ V) are listed in the most right column of the flow chart.**

These data were obtained with the tuning and matching controls of the PRC-74 set adjusted for relative maximum RF power output; i.e., in the case of PRC-74 whip, the full maximum available RF power of about 15 watts and corresponding whip foot point currents ranging from 390 mA to 410 mA. In the toroid case, toroid load currents were maximized by tuning both the matchbox capacitor and the PRC-74 set. Maximal toroid currents, achieved in this way with the toroid in air by itself, ranged from about 1.6 A to 2.0 A; dependent on proximity to vegetation along the road and the ground; maximal toroid currents on the tree in the jungle hole were 0.6 to 0.75 ampere and on the tree at the edge of the road 0.8 to 1.0 A, at corresponding 50% to 70% of full scale indications by the PRC-74 output meter.

In this connection, it is necessary to point out that the toroid tree matching circuit is designed to match the PRC-74 set to load impedances ranging from 1.5 ohms to 5 ohms; i.e., the empirically determined range of the equivalent series resistance of toroid coupled oak and pine forest trees in New Jersey. Comparing the toroid load current levels on the jungle trees with those on pine and oak trees (Fig. 2 and 3), one recognizes that the equivalent series resistances of jungle trees are most likely larger than those of pine and oak trees.

Since our Impedance Meter failed to work in the hot and humid tropical environment, the equivalent series load resistance of toroid coupled jungle trees could not be measured directly. Indirectly, however, these current levels, in conjunction with the results of a subsequent experiment involving a parallel tuned toroid circuit, yield the order of magnitude of the equivalent series resistance of toroid coupled jungle trees and, hence, an estimate of the degree of mismatch with the PRC-74 set.

* Input-output characteristics of this FET amplifier are given in Figure 13.

** The atmospheric noise levels given here are lower than the average, since measurements were made on different days and during times with relatively low and about equal atmospheric noise.

In contrast to the toroid coupled jungle trees, a practically perfect match between the PRC-74 set and the PRC-74 whip was achieved, not only when the vegetation was removed by machete within about a foot from the whip but also when a single leaf from the surrounding vegetation was touching the whip at about $2/3$ of its height. The operationally important implications are recognized when one considers, on the one hand, that one can hardly see the green painted PRC-74 whip in the green darkness of the jungle and, on the other hand, the severe loss of radiation from the whip at apparent full input power into the whip.

B.4 Indirect evaluation of the equivalent series load resistance of toroid coupled jungle trees (6 Sep 71).

Setup: This evaluation was carried out on 4.650 MHz with the toroid coupled jungle tree as radiator at the edge of the road in conjunction with the URM-85 whip receiver in the clearing 0.2 mile away.

Instead of the standard series tuned matchbox an especially for this purpose devised parallel tuned matchbox circuit was used (Fig. 11). The toroid on the tree becomes, in this circuit, a resonant auto transformer of which from two to three turns are connected across the output terminals of the PRC-74 set to match the oak and pine forest trees in New Jersey.

Results: Changing the toroid tap upward from three to five turns improved the match between the jungle tree and the PRC-74 set, and produced a corresponding increase by 5 dB in the transmitted signal strength measured 0.2 mile away with the URM-85 whip. The 5 turn tap represents the practical upper limit in the parallel tuned 12 turn toroid circuit. Nevertheless, the results of this experiment in conjunction with the previously described toroid load current levels confirm that the equivalent series resistance of jungle trees is higher than those of the oak and pine forest trees in New Jersey. Since impedance transformation by auto transformer action is proportional to the square of the tapped turns-ratios, one can estimate the equivalent series resistances of jungle trees to be about 3 to 4 times larger than those of the oak and pine trees in New Jersey.

The implications of this finding with regard to the impedance range of toroid-matching circuits for jungle trees are discussed later in this report.

B.5 Palm Tree Versus Jungle Trees (8 Sep 71)

Palms belong to a plant group with grasses, lillies, and orchids; as such palm (palmacea) are vegetables rather than trees. The trunk of palm trees have a pithy center but no growth rings or bark.

Similarly, many so-called jungle trees are not trees but ferns which are direct descendants from the ferns of the coal age. By virtue of their structures, ferns and palms are expected to be less efficient as natural radio antennas than are actual trees.

A man-planted large palm tree on the road 0.9 mile from Chiva Chiva did at least not contradict what could be expected from a vegetable antenna. Using the whip as common reference, radiation from the isolated palm tree turned out to be 6 to 9 dB lower than from the jungle trees in the jungle hole site.

APPENDIX C: MEASUREMENTS AT THE GAMBOA A.2 TEST AREA OF THE DECAYS VERSUS
DISTANCE IN WET AND DRY JUNGLE COVERED TERRAIN OF 4.650 MHZ
SIGNALS EMITTED AND RECEIVED BY WHIP AND JUNGLE TREE ANTENNAS
(5, 7, 8, SEP 71)

A divergence between the decays with distance of signals radiated from the PRC-74 whip and from toroid coupled jungle trees has been measured before at the Chiva Chiva Test Area (Fig. 16).

The subsequently described measurements in the Gamboa A.2 Jungle Area were carried out to investigate further the influence of the whip and of toroid coupled jungle tree antennas on RF signal propagation and to determine to what extent the relative dryness and wetness of the jungle vegetation affects the RF attenuation.

Measurement Setups: On the map of the Gamboa Test Area in Figure 17 are marked the transmitter XMTR and the receiver locations R₁ to R₆ along the jungle road where signal decays versus distance were measured for 4.650 MHz CW transmissions from: Whip to Whip; Whip to Trees; Tree to Whip; Tree to Trees. The measurements were made initially on 5 Sep in rainy weather and after heavy rainfalls when the jungle vegetation was dripping wet; they were repeated on 7 Sep before and during a thunderstorm, and on 8 Sep during hot and sunny weather when the surfaces of the vegetation were relatively dry.

The 4.650 MHz signals were transmitted from the PRC-74 whip on the jungle road and from a toroid coupled jungle tree about 20 feet away at the side of the road.

The whip was powered by a PRC-74 set, whereas, the toroid coupled jungle tree was powered by the lab constructed single tube XTAL controlled radio transmitter. Since our second PRC-74 set was needed by the receiver party to maintain communications while moving along the jungle road, the use of the tube transmitter avoided time consuming changes of connections to whip and toroid and eliminated the possibility of human error in resetting the respective tuning and matching conditions.* A picture of the PRC-74 whip and the toroid coupled jungle tree transmitter setups are shown in Figure 23.

Similarly, as in the Chiva Chiva Test Area, the radiated signals were received and measured with the URM-85 RFI Analyzer-Field Strength Meter connected to either the tripod mounted URM-85 whip on the road or to toroid coupled jungle trees at the edge of the road. A typical receiver setup is seen in the picture in Figure 24 where one may recognize the toroid coupled tree on the right side of the road behind the Landrover vehicle.

With the URM-85 set mounted in the Landrover vehicle, measurements were made at intervals of 0.5 mile up to 3 miles distance along the road, i.e., from 0.4 up to 2.5 miles air line distance from the XMTR site.

* Acoustical noise from the small gasoline driven ac generator which powered the tube transmitter helped to keep wild animals away from the transmitter site.

In the 5 Sep measurements, the toroid tree transmitter output was adjusted so as to produce at 0.4 mile distance about same signal field strength as the PRC-74 Whip Transmitter; signal field strength was measured for this purpose with the URM-85 Whip.

The same settings of the controls of the toroid coupled tree transmitter (Fig. 23) were reproduced again on 8 Sep. Instead of the regular flexible toroid with nominal 8" coil-diameter, a larger rigid toroid with 13" coil-diameter was employed for transmission on 7 Sep. For this larger toroid, the same 0.4 mile signal level equalization adjustments were made as before on 5 Sep for the smaller toroid.* Otherwise, deployments of equipments and the trees used were identical in all cases.**

Results: The data obtained under relatively low atmospheric noise conditions in the dripping wet and the dry jungle on respectively 5 Sep and 8 Sep are given in Figures 18 and 19. The data, partially corrupted by lightning noise from 7 Sep are given in Figure 20.

Plotted in these figures are along the absciss, the air mile distance between the XMTR site and the receiver locations, and along the ordinate the noise levels and the signal noise levels as measured in decibels above 1 μ V with the URM-85 set for 4.650 MHz CW transmissions from: Whip to Whip; Tree to Whip; Whip to Trees; and Trees to Trees.

The 7 Sep thunderstorm and heavy rain inhibited the completion of measurements over the full distance range, yet the resultant data correlate in a rather dramatic way with the 5 Sep and 8 Sep data.

In this respect, consider on the one hand that at 1.7 mile distance from the transmitter site only the tree to tree transmissions came through above the lightning noise levels during the 7 Sep thunderstorm (Fig. 20).

On the other hand, note that the signal + noise levels received by toroid coupled trees in the dripping wet jungle on 5 Sep (Fig. 18) have at 1.7 mile distance relative maxima which are 22 dB and 20 dB above the S + N levels received with the whip. Consider further, the divergent shapes of the whip and the tree curves in the dripping wet jungle case, 5 Sep (Fig. 18), in contrast with the initial and the overall conformance of the tree and whip curves from 7 Sep (Fig. 20) and 8 Sep (Fig. 19), respectively.***

* The larger rigid toroid represents a piece of an original 22 turn MF toroid which was cut up for this purpose.

** AC power from the Zeus generators for the tree transmitter and for the URM-85 set was controlled and measured in each case to give 120 volts at 60 Hz.

*** A similar divergency has been measured before at Chiva Chiva (Fig. 16).

Evidently the thunderstorm noise on 7 Sep did not only cover up the signal minima at 1.3 miles distance, but the accompanying rain changed the RF propagation conditions towards those experienced in the dripping wet jungle on 5 Sep.

The drastically different type of signal decays with distance as sensed with the whip and with toroid coupled trees in the dripping wet and in the dry jungle is quantified by the corresponding $\frac{S+N}{N}$ ratio versus distance curves in Figures 21 and 22.

These curves conform respectively to an x^{-3} and an $e^{-0.5 x^2}$ type law within the measurement range $0.4 \leq x \leq 2.5$ miles.

The influence of the terrain on the shape of the signal decay versus distance curves can be deduced from the terrain profiles which are plotted in Figures 30 to 35. In particular, over only 1.3 air miles (Fig. 32), voice communications by the whip equipped PRC-74 sets of XMTR and receiver party was hardly understandable as the voice signal levels on both ends faded almost into the relative low noise backgrounds on 5 Sep. and 8 Sep. (On 7 Sep., lightning noise blocked voice communications completely.)

This fadeout of the whip to whip voice communications correlates with the 1.3 mile dips of the signal decay versus distance curves measured with the URM-85 meter. (Fig. 21 and 22.)

A comparison of these curves with the terrain profiles (Fig. 30 to 35) shows that the obstructing influence of the hilly terrain is felt more severely in the dripping wet jungle (5 Sep, Fig. 21) than in the dry jungle (8 Sep, Fig. 22) and, in all cases (7 Sep, Fig. 20 included), more severely by the whip than by the toroid coupled trees.

Considering the results from the previously mentioned modeling experiments in connection with the data from Chiva Chiva (Fig. 16) and from Gamboa (Fig. 19 to 22), one must conclude that the superior performance of the trees is in a large part due to their ability to produce and to sense the dominant horizontal polarization, i.e., the polarization with the greater survival rate in the dominant vertically structured roughness of terrain and vegetation. * and **

* Peter Beckmann and Andre Spizzichino, "The Scattering of Electromagnetic Waves from Rough Surfaces," International Monograph on Electromagnetic Waves, Vol. 4, Publ: Oxford, Pergamon N.Y., McMillan Co., 1964, 1963.

** W. Gerber and A. Wertmüller, "Absorption of Groundwaves by Vegetation" (Über die vegetabile Absorption der Bodenwelle), Technical Bulletin of the Swiss Telegraph and Telephon Administration (Technische Mitteilungen der Schweiz. Telegraphen und Telephonverwaltung) Jg. XXIII, 1945, No. 1.

APPENDIX D: PHENOMENOLOGICAL INTERPRETATION OF EXPERIMENTAL RESULTS

Development of field equipment from experimental devices and of operating guidelines from experimental data requires an understanding of the phenomena which help and or hinder the achievement of technical objectives, i.e., tactical radio communications in tropical jungle terrains.

The phenomena which govern radio emission and reception at ground locations in jungle forests are easily recognized by considering the jungle as a maze of aperture coupled screen rooms as they are used for radio interference reduction. In the jungle case, the screens, i.e., vertical tree and fern trunks and the horizontal canopy, are of variable thickness, and have variable shaped apertures in different materials which contain mostly water.

D.1 Direct RF Leakage Radiation

Invoking the designation of a whip antenna as a monopole, the quasi-static near field lines emanating from a whip can be drawn by connecting a concentrated monopole charge with its distributed counter charge on the surface of the surrounding vegetation and the ground. The larger the number of field lines that leak through the apertures in the canopy and terminate on the top of the canopy, the larger is the radiation from the whip; hence, the operation of the whip in jungle vegetation depends on direct leakage radiation via apertures; and, in practice, also on the ability to tune and match the XMTR to respectively the reactive and resistive partial loading by the vegetation.

While the sizes of the apertures in the jungle canopy are, therefore, important, the relative wetness and dryness of the vegetation determines whether the surface charges are really on the surface or actually under the surface of the vegetation (Gamboa Data (Figures 22 and 23)).

The field lines that emanate from the monopole antenna and, in particular, the leakage field lines terminate then on respectively a good and bad ground.

Similarly, as for the XMTR whip, one can deduce the performance of the receiver whip from the monopole model.

For this purpose, one employs the principle of action and reaction to the incident field and the monopole field.

It follows that the interaction of the whip with the incident field will be weak and the received signal low when the incident field lines and the monopole field lines are largely divergent.

D.2 Indirect RF Leakage Radiation

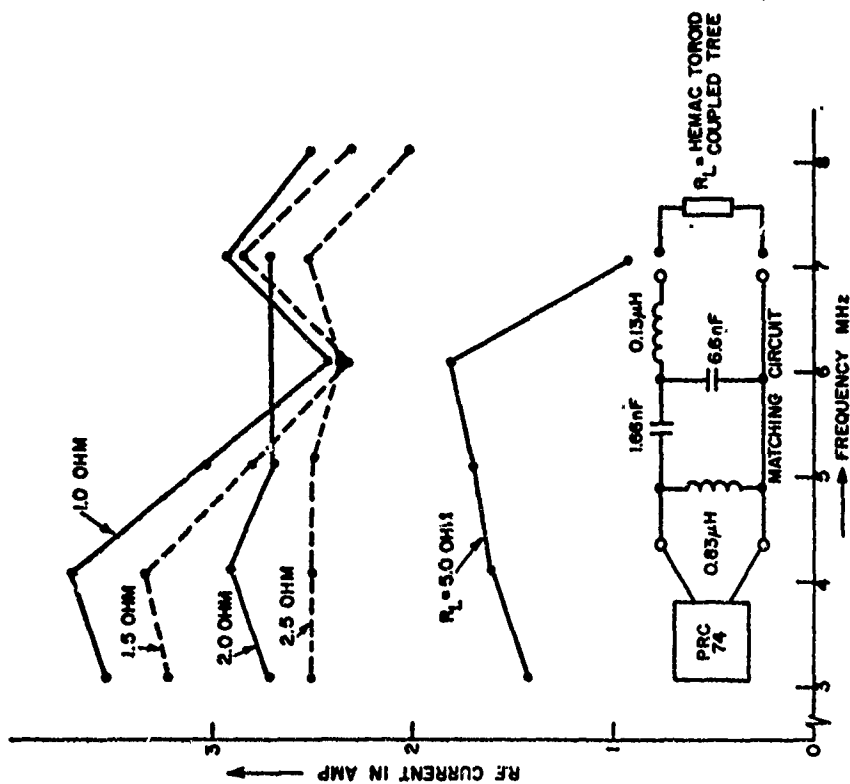
Citing again the screen room maze analogy for the jungle, and the fact that screen room leakage radiation can be stimulated by induction of RF

currents in the walls and the ceilings of the screen rooms, one recognizes the roles assigned to HEMAC toroid coupled trees; the tree trunk is just a convenient wall inlet for induction of RF currents that loop through the canopy; similarly, in the receiver case, tree trunks are convenient outlets to tap into the loop currents which are excited by the incident radio waves.

Insofar as the HEMAC toroid is primarily a transformer and not a radiator like the whip, the induced magnetic dipole and multipole type radiation from natural tree loops is referred to as indirect leakage radiation.



FIG. 1 PRC-7h Transceiver Set
Connected Via Series Tuned
Impedance Matching - Meter Box
to HEMAC Toroid
Wayside N.J. Area April 1971



PRC-74 RF CURRENT VS. FREQUENCY INTO EQUIVALENT RESISTANCES R_L OF TOROID (HEMAC) COUPLED TREES IN N.J.—OCT. 27, 1970.

FIG. 2 PRC-74 RF Current Vs. Frequency Into Equivalent Resistances R_L Of Toroid (HEMAC) Coupled Trees in N.J.

October 27, 1970

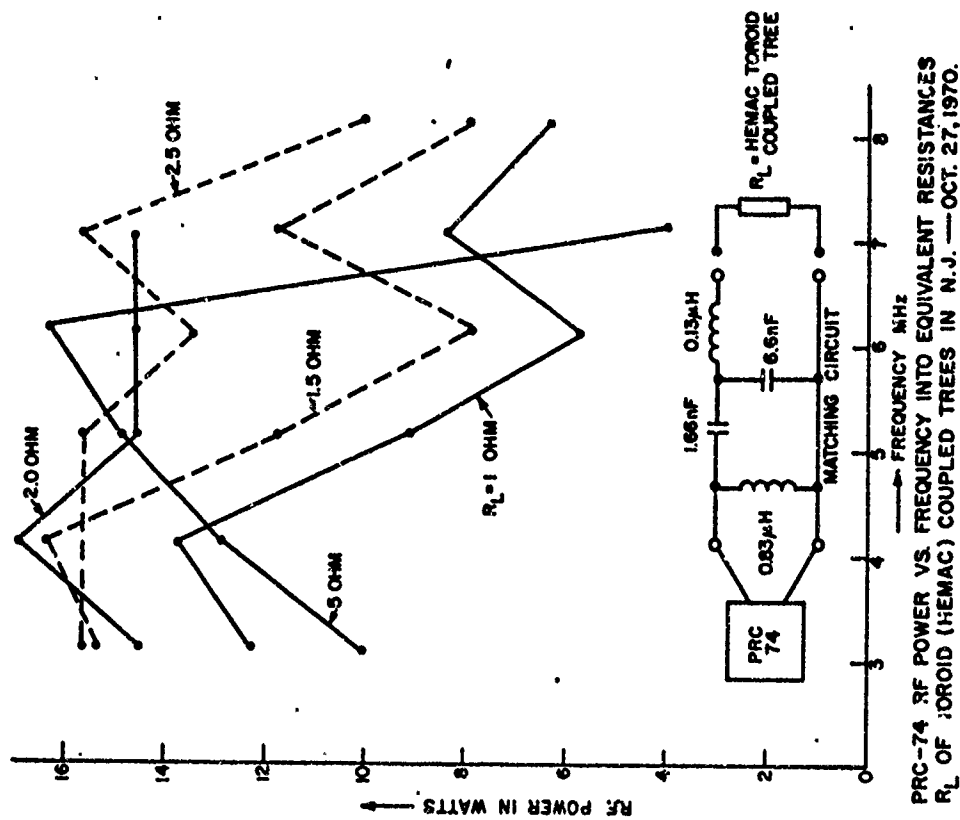


FIG. 3 PRC-74 RF POWER VS. FREQUENCY INTO EQUIVALENT RESISTANCES R_L OF TOROID (HEMAC) COUPLED TREES IN N.J. — OCT. 27, 1970.

FIG. 3 PRC-74 RF Power Vs. Frequency
Into Equivalent Resistances R_L
Of Toroid (HEMAC) Coupled
Trees In N.J. October 27, 1970



FIG. 4 Jungle Forest
Gamboa A-2 Area
Panama C.Z. September 71



FIG. 5 Jungle Underbrush Vegetation

Chiva Chiva Area, Panama C.Z.
-- September 71



FIG. 6 URN-85 (RFI-Analyzer) Field
Strength Meter + Whip Antenna
Chiva Chiva Area, Panama C.Z.
September 71



FIG. 7 HEMAC Toroid Coupled Tree and
PRC-74 Set At Jungle Hole Site
Chiva Chiva Area, Panama C.Z.
September 71

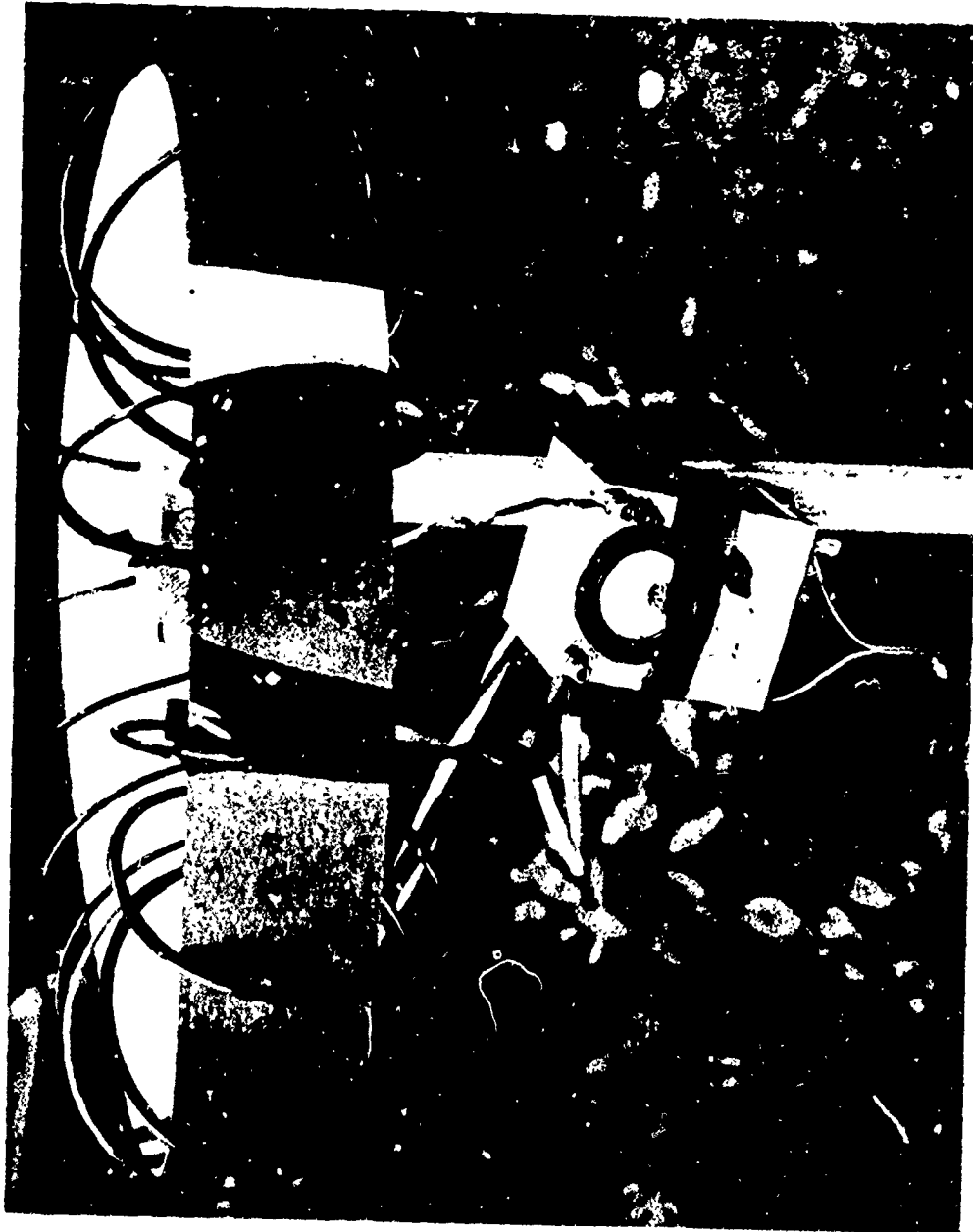


FIG. 8 HEMAC Toroid In Air At Road
Chiva Chiva Area, Panama C.Z.
September 71



FIG. 9 PRC-74 Set + Whip At Jungle
Hole Site
Chiva Chiva Area, Panama C.Z.
September 71

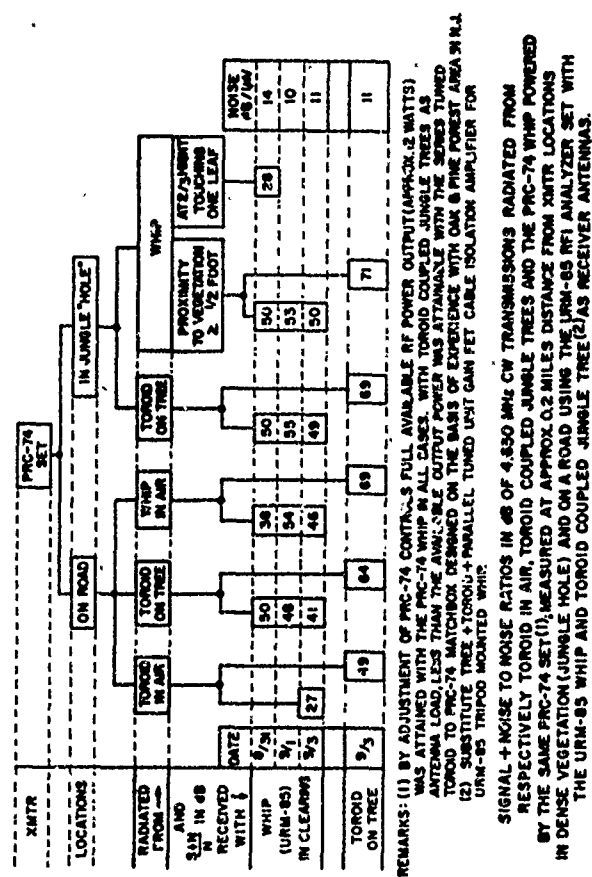


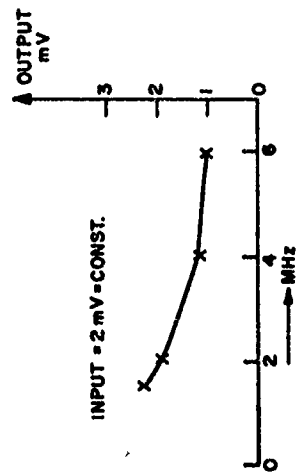
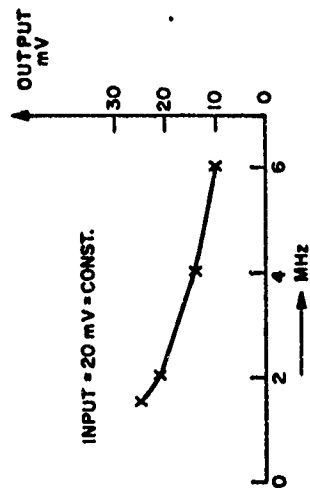
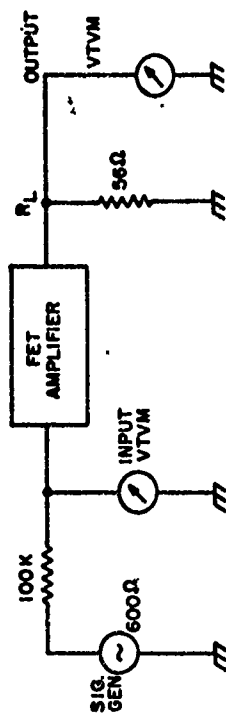
FIG. 10 Signal + Noise to Noise Ratios
In dB Of 4.650 Mhz CW Trans-
missions
Chiwa Chiwa Area, Panama C.Z.
September 7.



FIG. 11 Improvised Shunt Tuned Auto
Trafo Type HEMAC + Tree to
PAC-74 Set Matching Circuit
Chiva Chiva Area, Panama C.Z.
September 71



FIG. 12 HEMAC Toroid Coupled Tree -
UTM-85 Meter (Receiver Set-up)
Chiva Chiva Area, Panama C.Z.
September 71



CALIBRATION OF TOROID (HEMAC) TO CABLE ISOLATION FET AMPLIFIER

FIG. 13 Calibration of Toroid (HEMAC) To Cable Isolation FET Amplifier



FIG. 14 URM-85 Whip (Receiver Set-up)

Chiva Chiva Area, Panama C.Z.
September 71

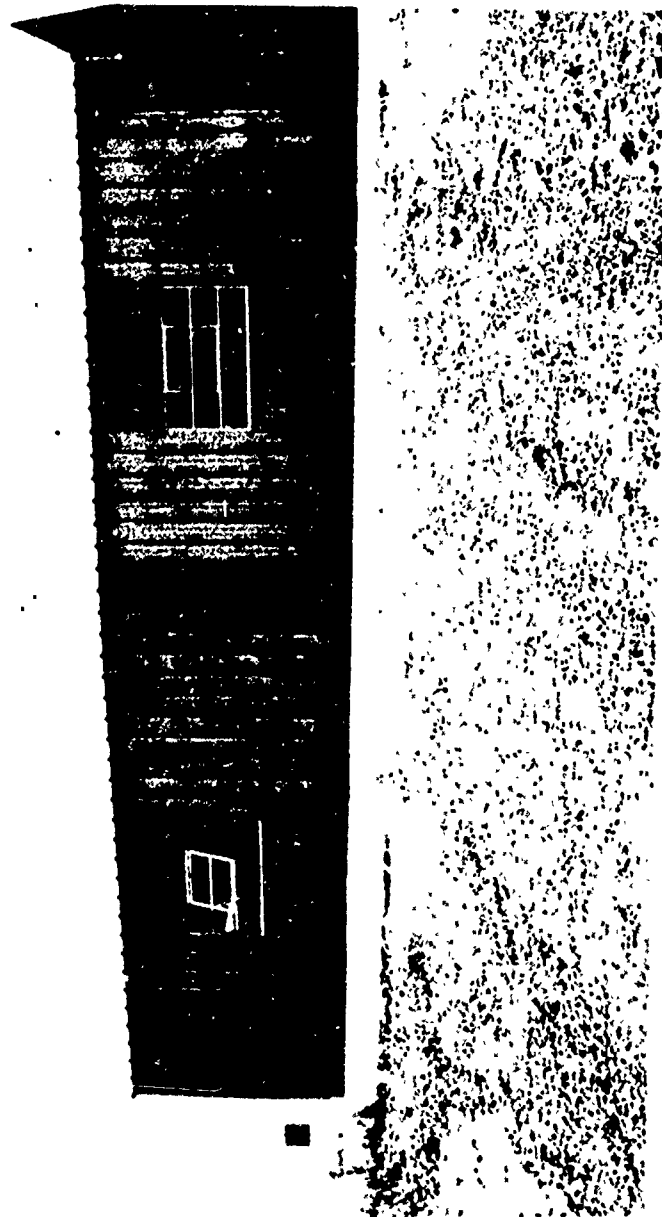
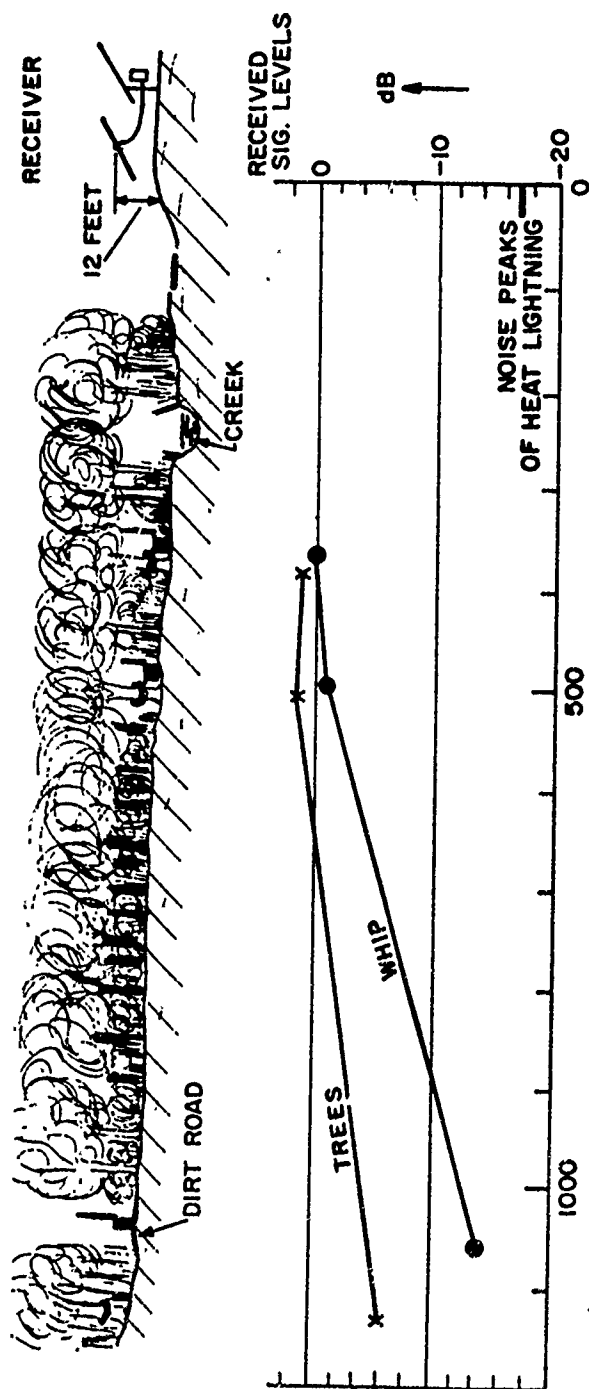


FIG. 15 Horizontal Wire Dipole Antenna
(40 meter band)
Chiva Chiva Area, Panama C-2.
September '71



FOOTNOTES: (1) HOR. REC. DIPOLE CUT FOR 8.050 MHz
 (2) VIA. SERIES TUNED MATCHBOX.
 (3) TUNE-MATCHING CONTROLS ADJUSTED IN EACH CASE
 FOR MAX. POSSIBLE RF OUTPUT INDICATION BY PRC-74 METER.

RELATIVE LEVELS IN dB AS RECEIVED
 WITH HORIZONTAL WIRE DIPOLE ANTENNA (1)
 OF 4.650 MHz CW SIGNALS RADIATED FROM
 RESPECTIVELY THE PRC-74 WHIP AND HEMAC
 TOROID COUPLED JUNGLE TREES (2) POWERED
 BY IDENTICAL PRC-74 TRANSCIVER SET (3).

CHIVA-CHIVA TEST AREA 8/26/71

FIG. 16 Relative Levels In dB As
 Received With Horizontal Wire
 Dipole Antenna of 4.000 MHz
 CW Signals Radiated From
 Respectively the PRC-74 Whip
 And HEMAC Toroid Coupled Jungle
 Trees Powered by Identical
 PRC-74

Chiva Chiva Area September 71



Panama C.Z.

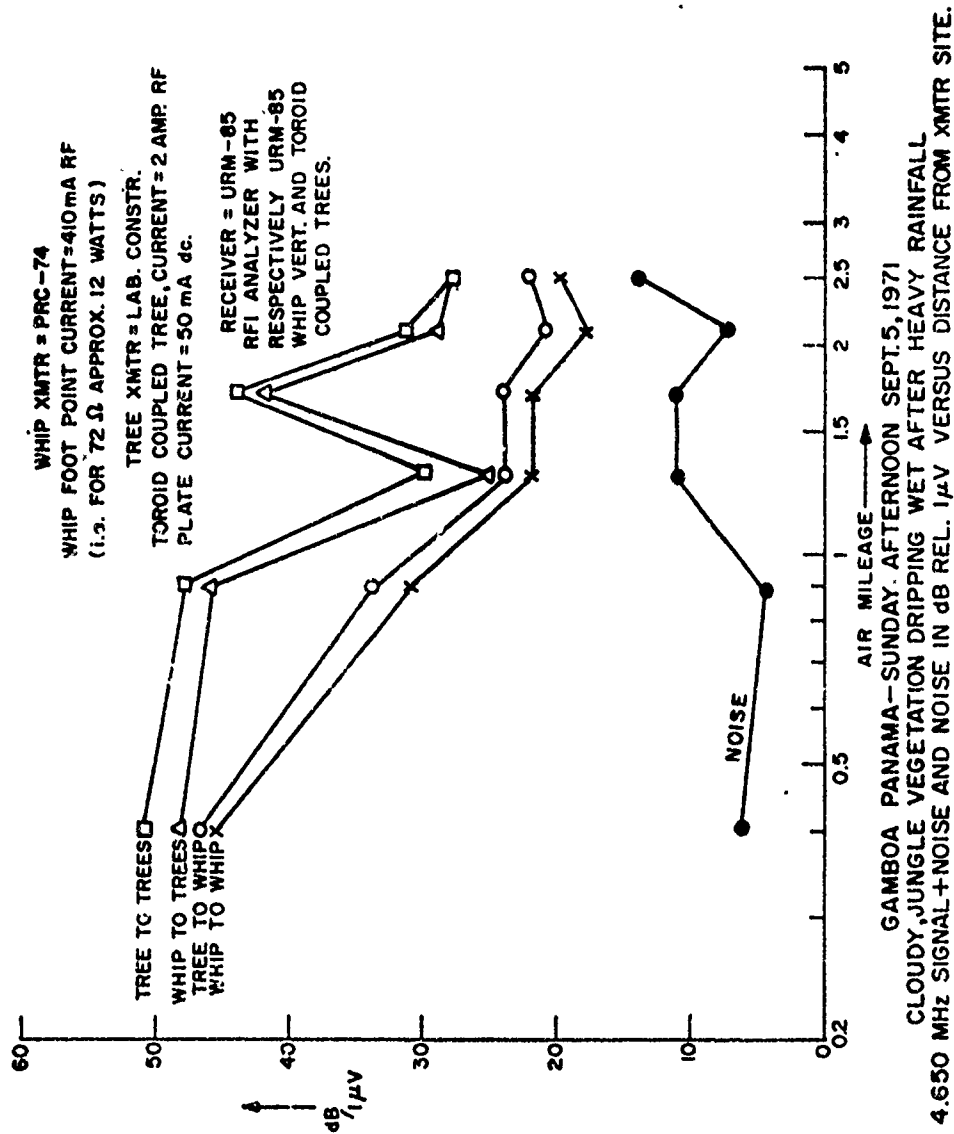
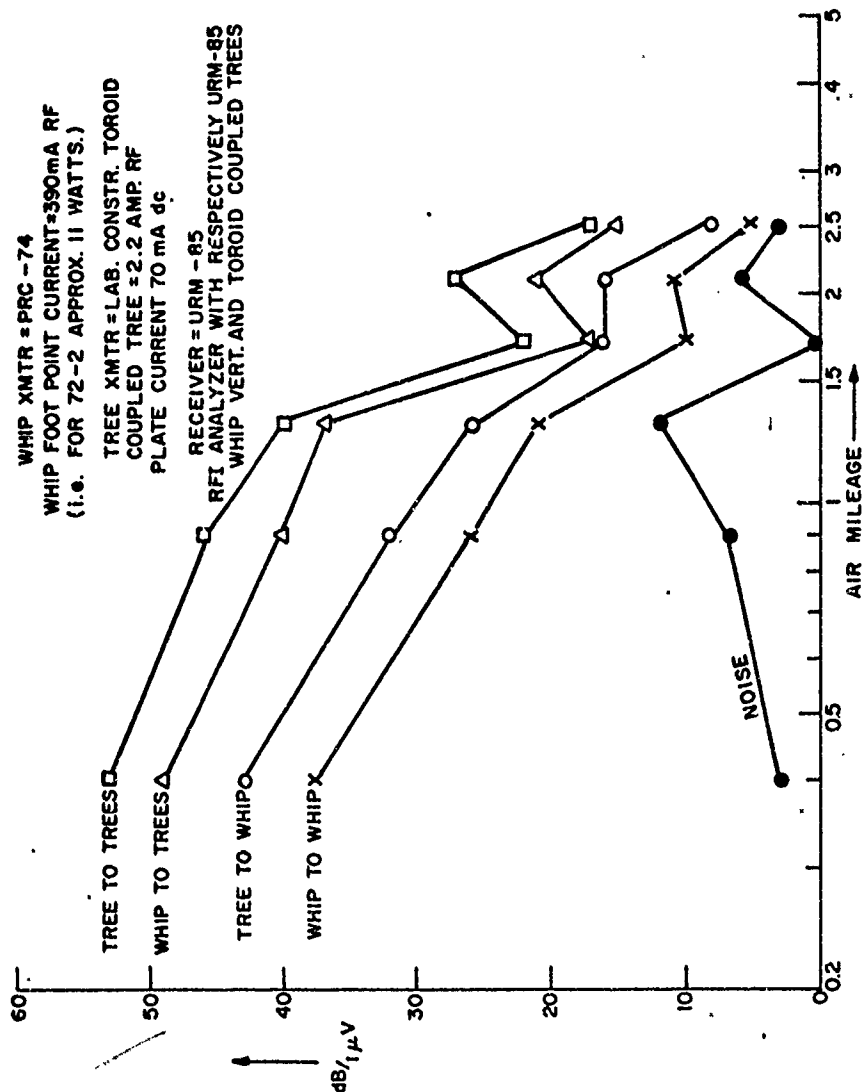


FIG. 18 4.650 Mhz Signal + Noise And
Noise in dB Rel. $1 \mu V$ Versus
Distance from XMTR Site. Jungle
Vegetation Dripping Wet
Gamboa A2 Area, Panama C.Z.
September 5, 71



GAMBOA PANAMA - WEDNESDAY - BEFORE NOON SEPT. 8, 1971
SUNNY, JUNGLE VEGETATION SURFACES RELATIVELY DRY
4.650 MHz SIGNAL + NOISE IN dB REL. 1 μV VERSUS DISTANCE FROM XMTR SITE.

FIG. 19 4.650 MHz Signal + Noise In dB
Rel 1 μV Versus Distance From
XMTR Site. Jungle Vegetation
Dry.
Gamboa Area, Panama C. 8, 71

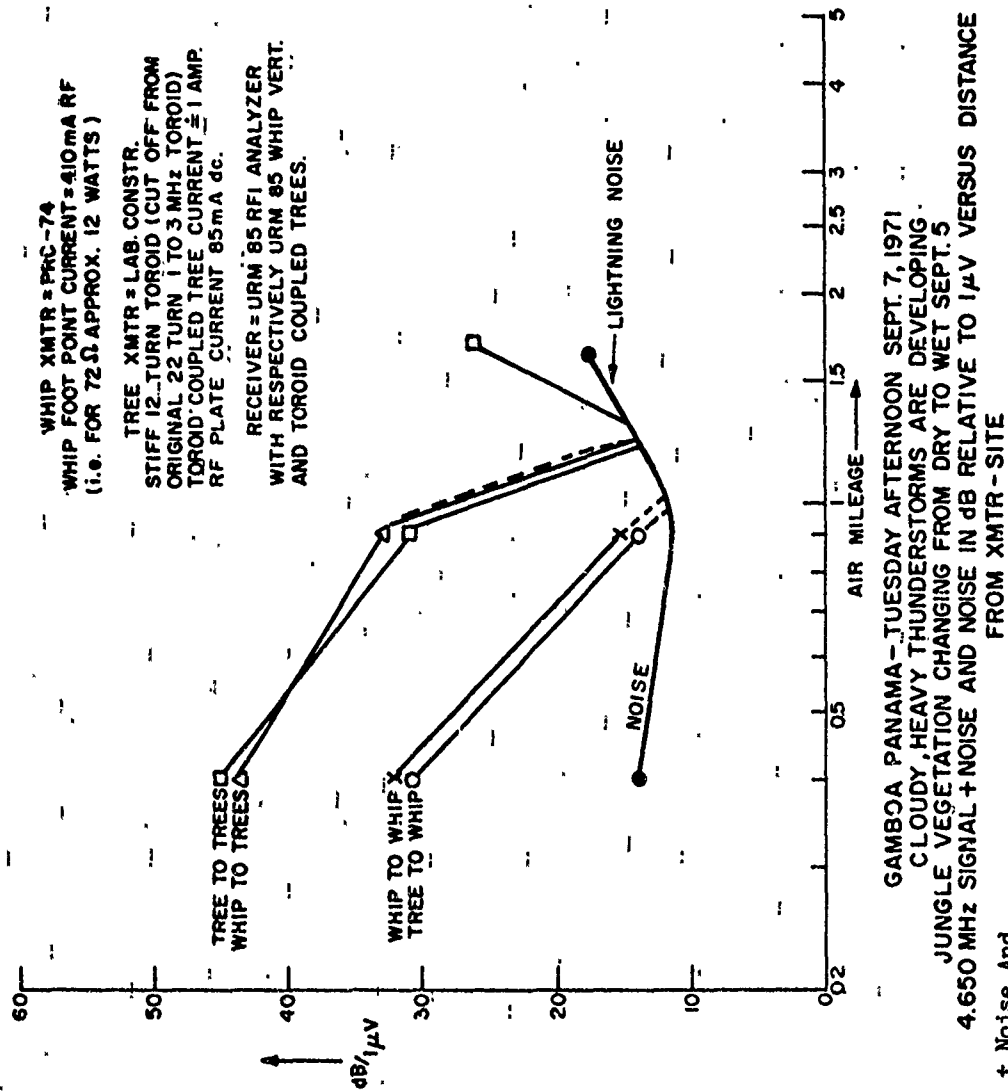
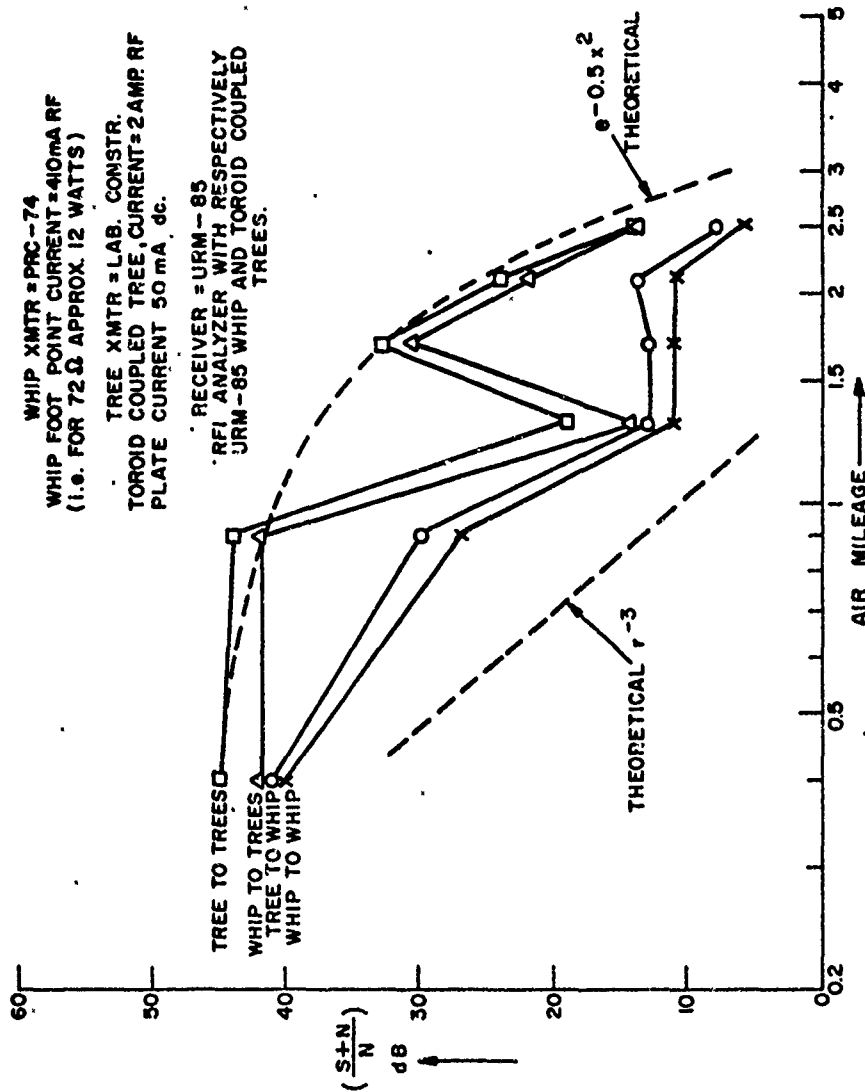


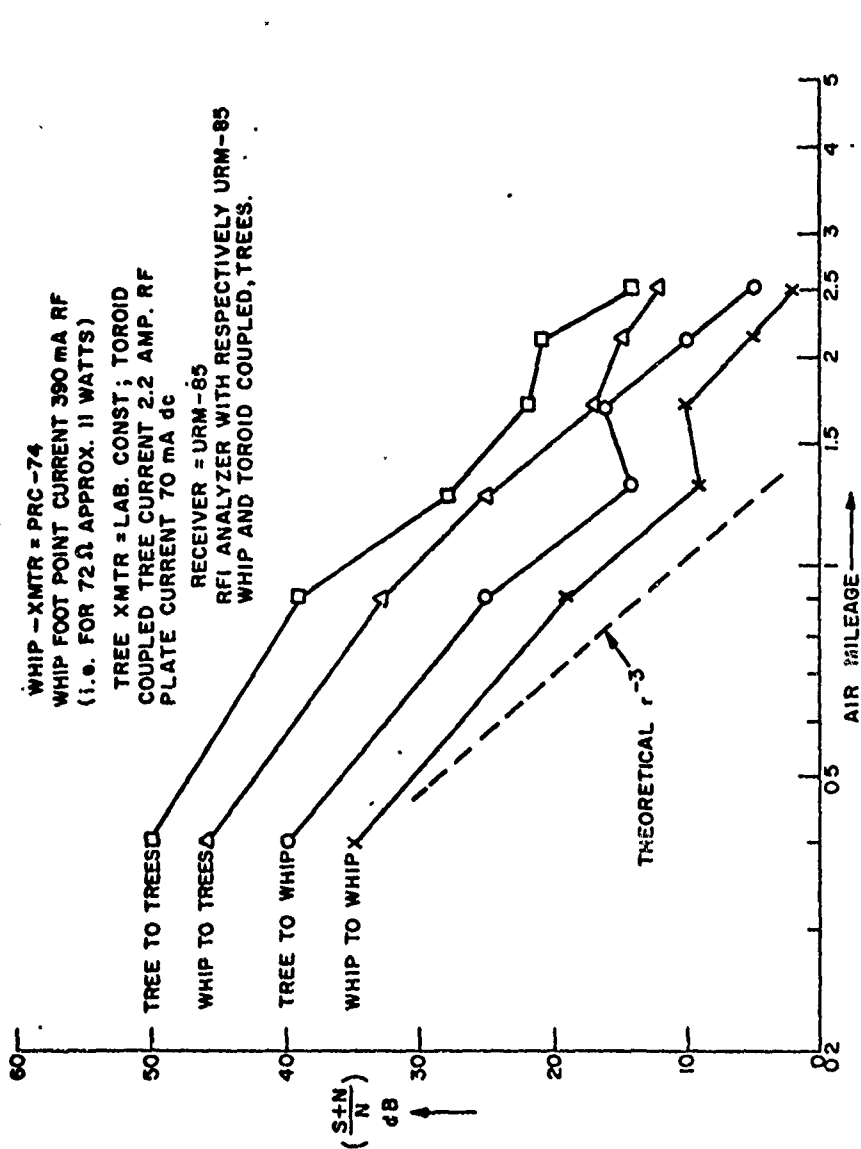
FIG. 20 4.650 MHz Signal + Noise And
Noise in dB Rel 1 μV Versus
Distance From XMTR Site. Jungle
Vegetation Changing From Dry To
Wet During Thunderstorm.
Gamboa Area, Panama C.Z.

September 7, 71



GAMBOA PANAMA - SUNDAY AFTERNOON SEPT 5, 1971
CLOUDY - JUNGLE VEGETATION DRIPPING WET AFTER HEAVY RAINFALL
4.650 MHz SIGNAL + NOISE/NOISE IN dB VERSUS DISTANCE FROM XMTR SITE.

FIG. 21 4.650 MHz Signal + Noise/Noise
In dB Versus Distance From XMTR
Site. Jungle Vegetation Dripping
Wet
Gamboa A-2 Area, Panama C.Z.
September 5, 71



GAMBOA PANAMA WEDNESDAY BEFORE NOON SEPT. 8, 1971
SUNNY, JUNGLE VEGETATION SURFACES RELATIVELY DRY
4.650 MHz SIGNAL+NOISE/NOISE IN dB VERSUS DISTANCE FROM XMTR SITE

FIG. 22 4.650 MHz Signal + Noise/Noise
In dB Versus Distance From XMTR
Site. Jungle Vegetation Dry.
Gamboa A.2 Area, Panama C.Z.
September 8, 71



FIG. 23 INTR-Site: PRC-74 Set + Whip And
HEMAC Toroid Coupled Tree With
Lab. Constr. INTR-Set.
Gamboa A-2 Area, Panama C.Z.
September, 71

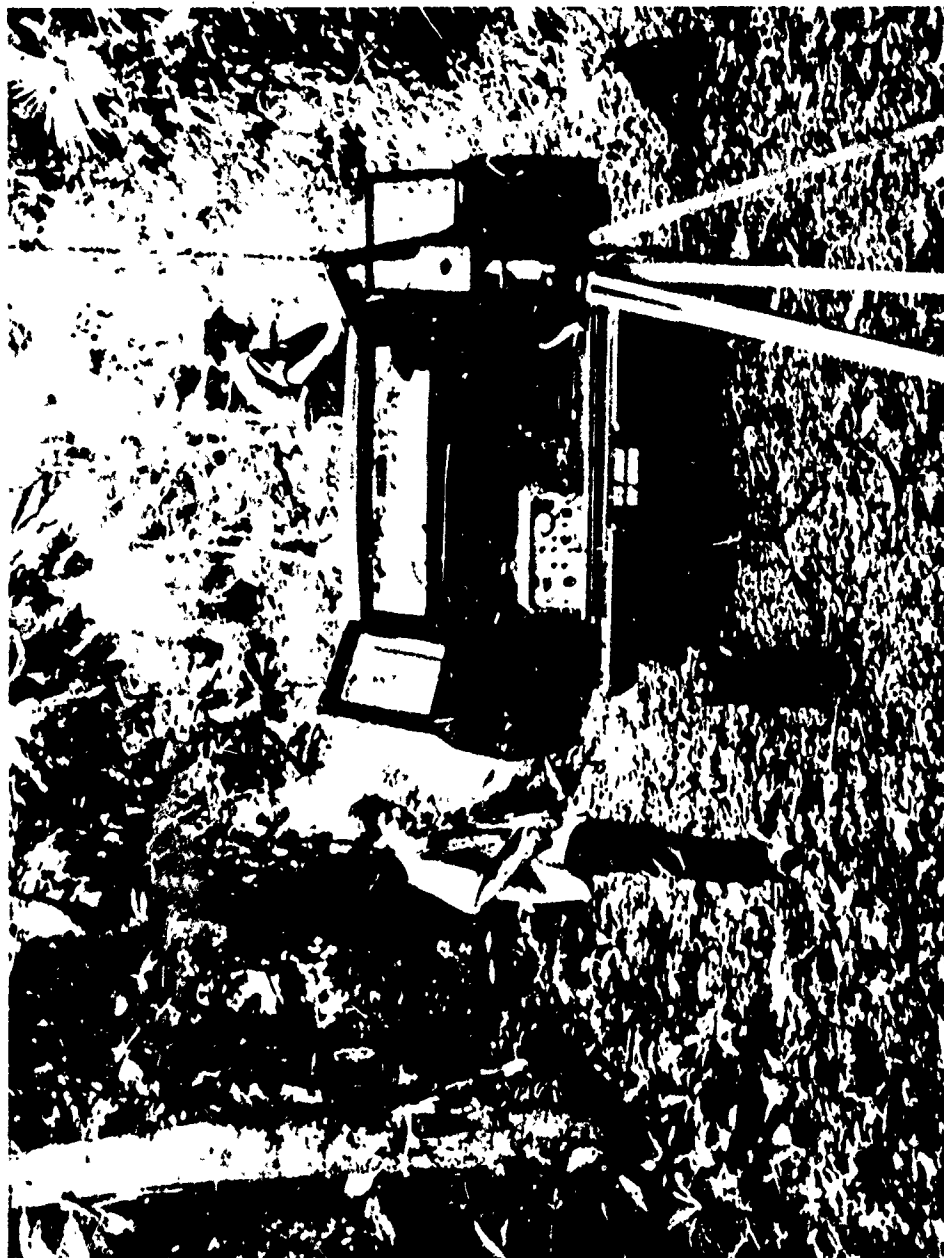


FIG. 24 Typical Receiver Set-up: From
Left To Right: HEMAC Toroid
Coupled Tree, PRC-711 Set + Whip,
URM-85 Field Strength Meter In
The Vehicle, URM-85 Whip On
Tripod.

Gamboa A.2 Area, Panama C.Z.
September, 71

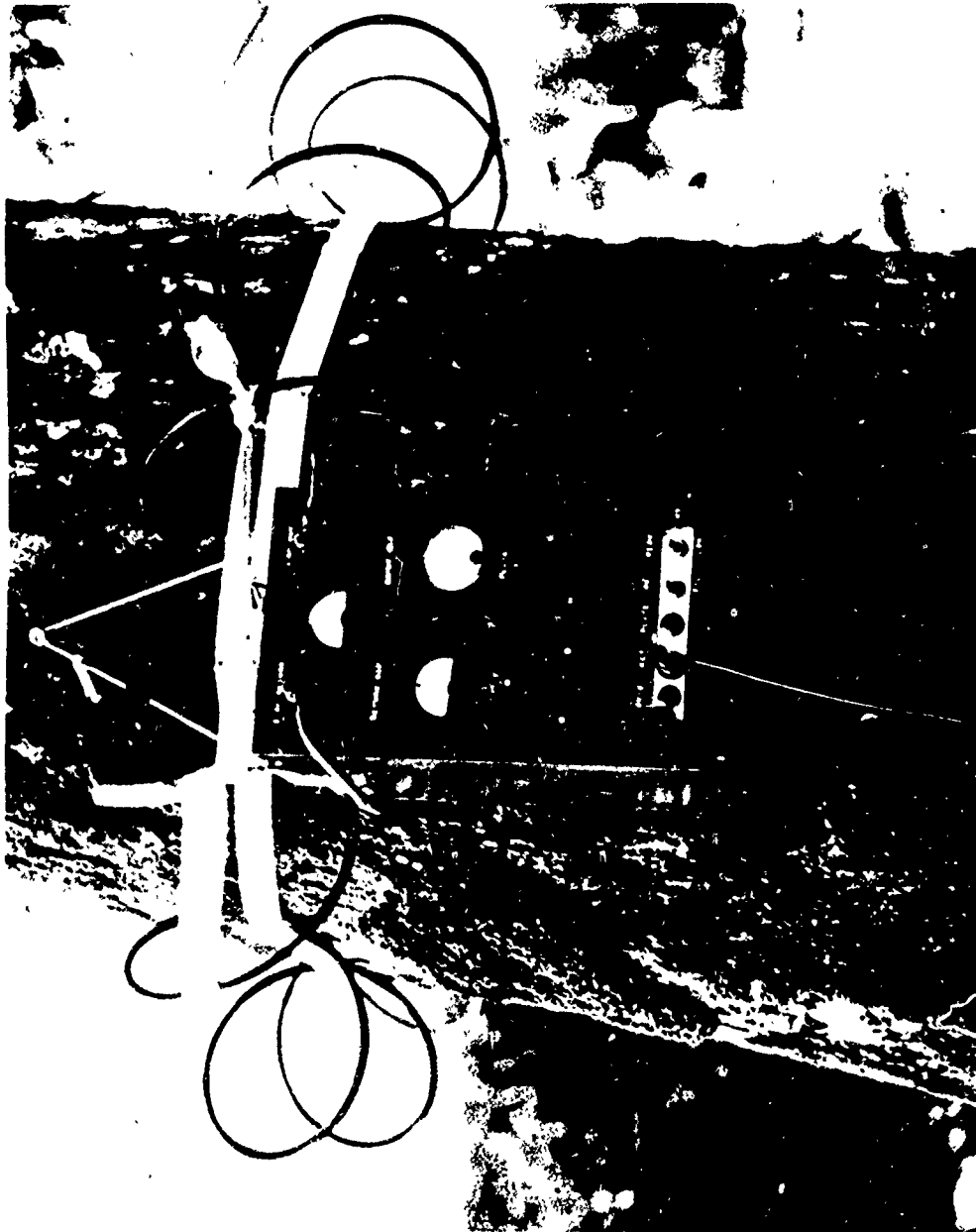


FIG. 25 HEMAC Toroid Coupled Large Tree
(4.650 MHz XWTR Set-up with 10
Mile Range)
Chiva Chiva Area, Panama C.Z.
September, 71



FIG. 26 Las Cruces Trail
Gamboa A.2 Area, Panama C.Z.
September, 71

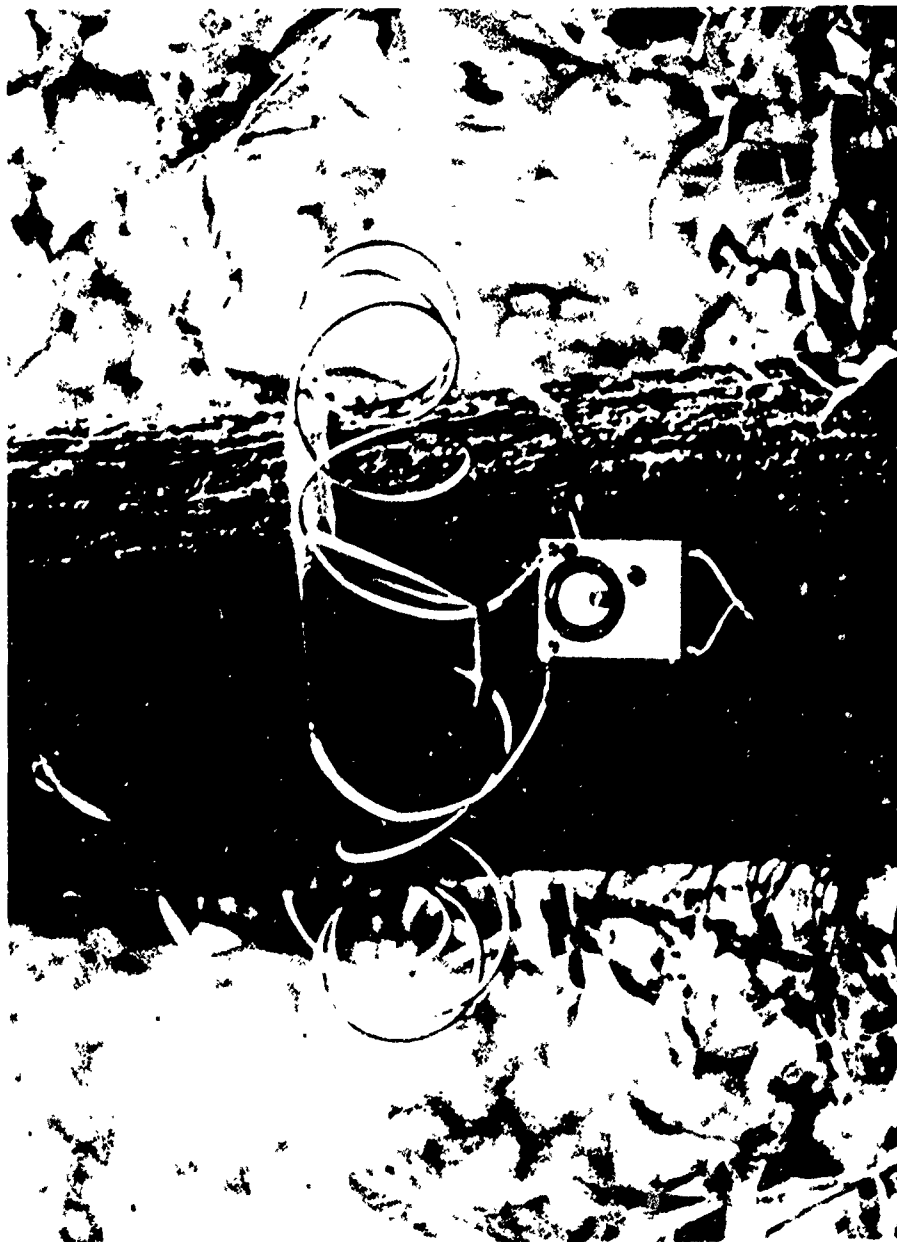


FIG. 27 HEMAC Toroid Coupled Tree On
Las Cruces Trail
Gamboa A-2 Area, Panama C.Z.
September, 71

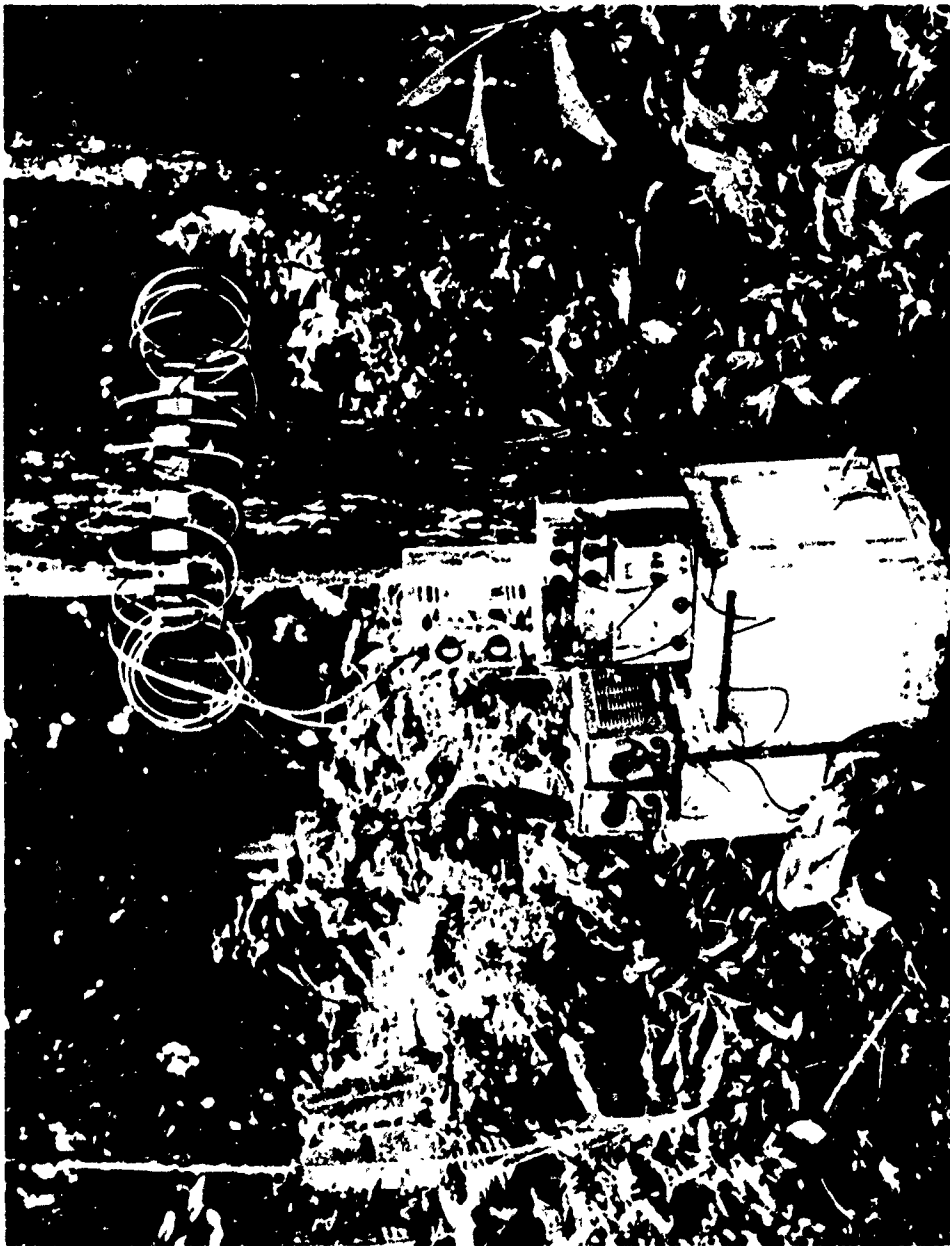


FIG. 28 HEMAC Toroid Coupled Large Tree-
410 kHz XMTR Set-Up Chiva
Chiva Area
Panama C.Z. September, 71

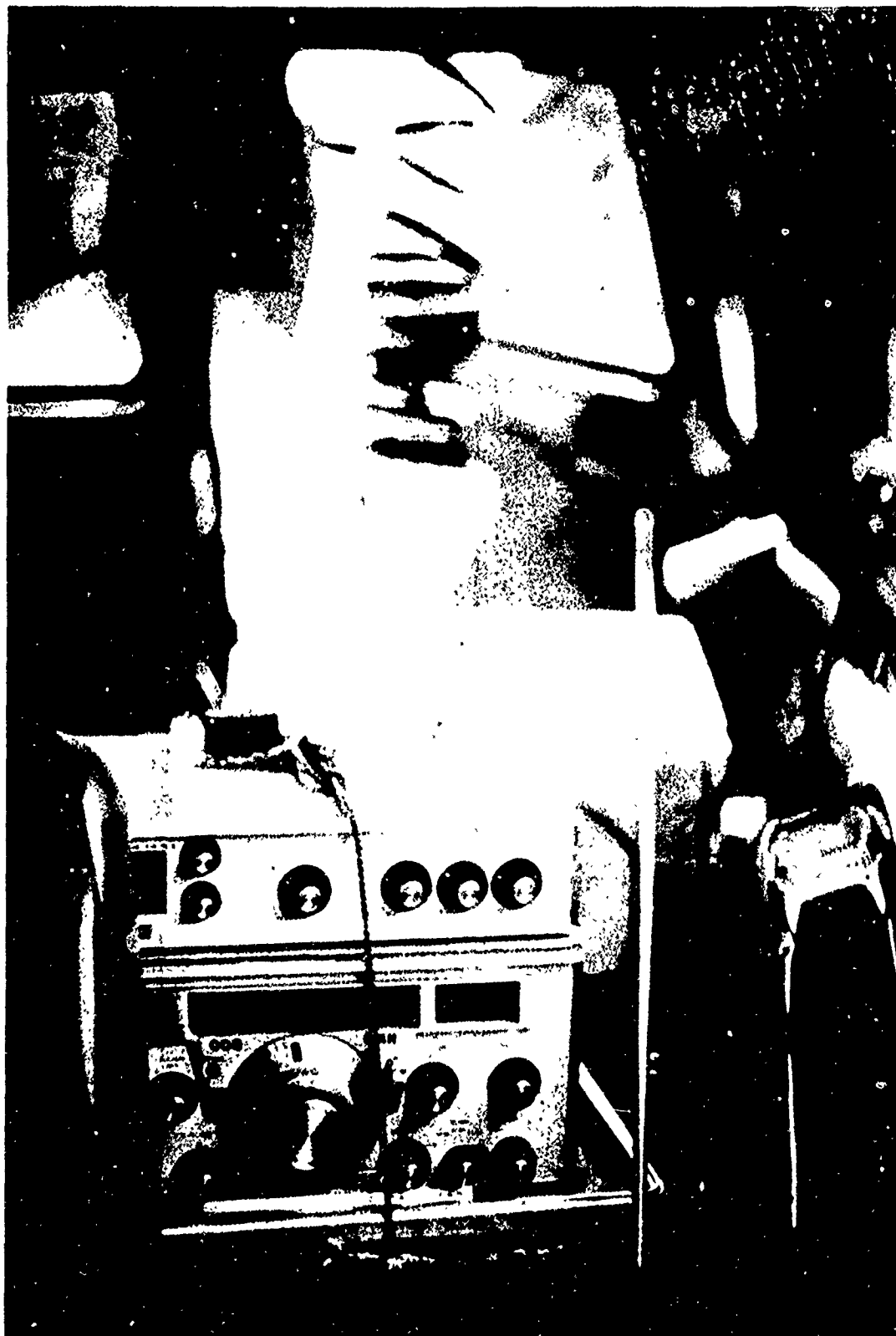


FIG. 29 410 kHz - (HRO-500) Receiver
Set-up In Land Rover Vehicle

GAMBOA A2
PANAMA CZ
TERRAIN PROFILE
XMTR - REC R₁

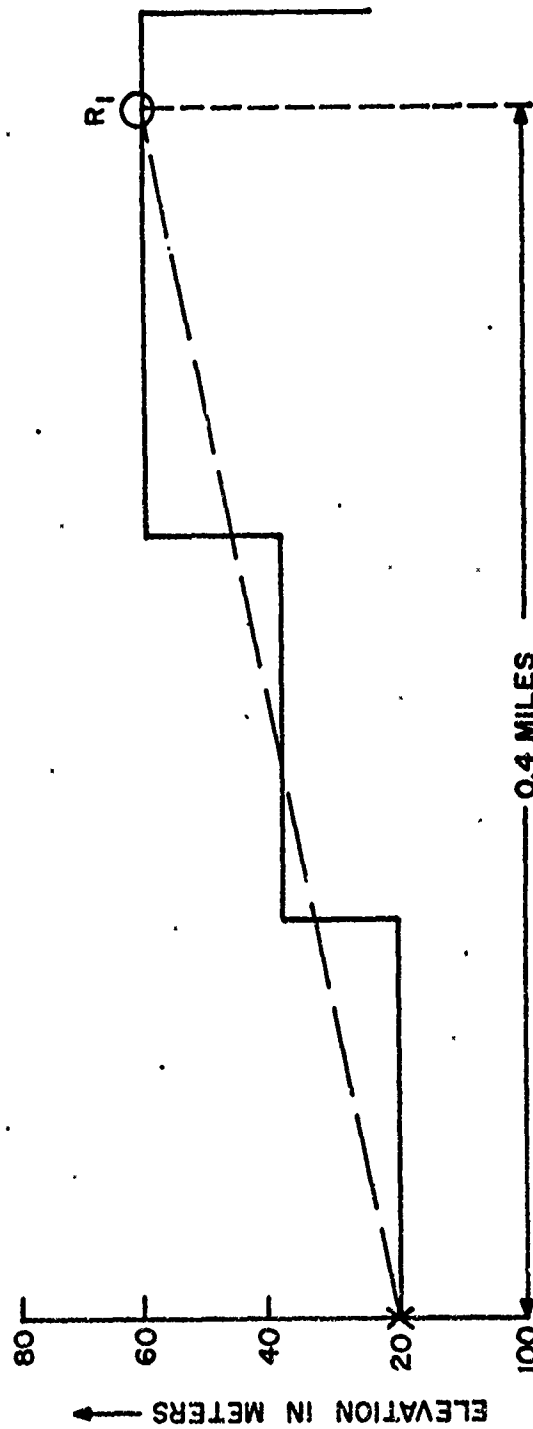


FIG. 30 Terrain Profile XMTR-REC. R₁

GAMBOA A2
PANAMA CZ
TERRAIN PROFILE
XMTR - REC R₂

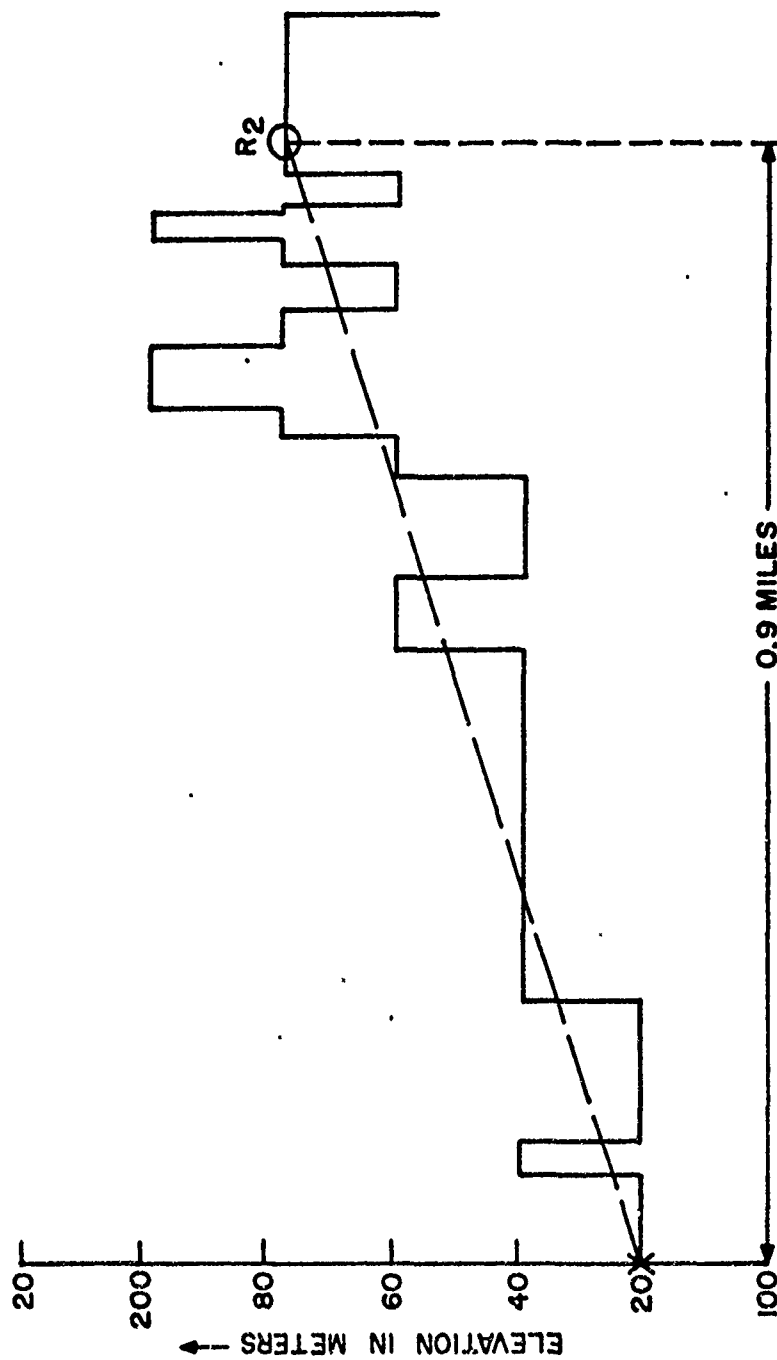


FIG. 31 Terrain Profile XMTR-REC. R₂

GAMBOA A2
PANAMA CZ
TERRAIN PROFILE
XMTR-REC R3

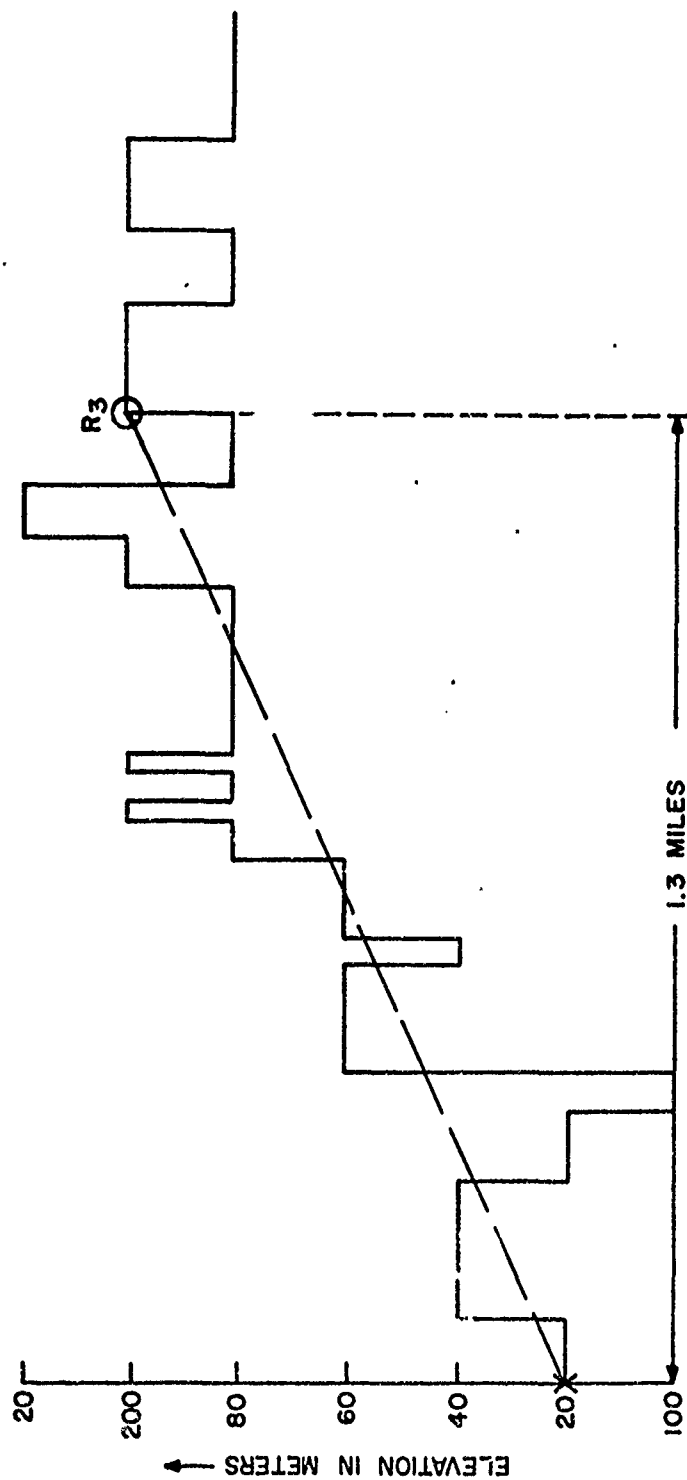


FIG. 32 Terrain Profile XMTR-REC. R3

GAMBOA A2
PANAMA CZ
TERRAIN PROFILE
XMTR - REC R4

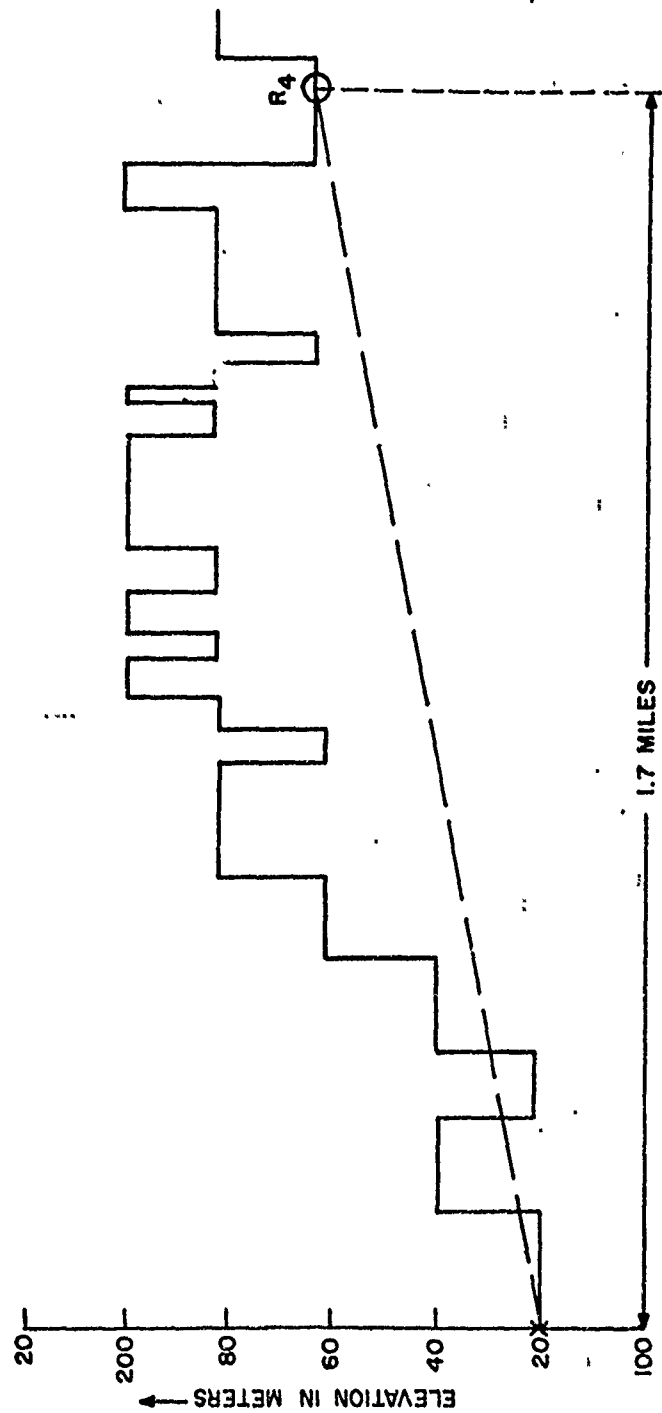


FIG. 33 Terrain Profile XMTR-REC. R4

GAMBOA A2
PANAMA CZ
TERRAIN PROFILE
XMTR-REC R5



FIG. 34 Terrain Profile XMTR-REC. R₅